Impact of Cladding on Mid-Rise Buildings in the Northridge Earthquake

by

Chuan-Hua Kuo

B.S. Civil Engineering
University of Texas at Austin
2007

Submitted to the Department of Civil and Environmental Engineering on May 8, 2009 in Partial Fulfillment of the Requirements for the degree of

Master of Engineering in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2009

Signature of Author: ______________________
Department of Civil and Environmental Engineering
May 8, 2009

Certified by: ______________________
Jerome J. Connor
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by: ______________________
Daniele Veneziano
Chairman, Departmental Committee for Graduate Students

Impact of Cladding on Mid-Rise Buildings in the Northridge Earthquake

By

Chuan-Hua Kuo

Submitted to the Department of Civil and Environmental Engineering on May 8, 2009 in Partial Fulfillment of the Requirements for the degree of Master of Engineering in Civil and Environmental Engineering

Abstract

In this thesis, the importance of cladding panels on mid-rise buildings in an earthquake-prone region is investigated. A cladding panel acts as a protective or an insulating layer to control weather infiltration. The Northridge Earthquake, which took place on January 17, 1994, caused numerous heavy cladding panels to fall off the walls of residential and commercial buildings. The failure of these panels was a result of an insufficient understanding of the cladding behaviors as a subsystem in the three-dimensional framing system.

Cladding is designed to be isolated from the structural frame movement during an earthquake. However, numerous studies have concluded that cladding interacts with the structural frame in providing lateral resistance. The advantages and disadvantages of different cladding materials, cladding systems, and cladding connections are presented in this thesis.

The effects of cladding on mid-rise buildings in the Northridge Earthquake in the Los Angeles area are simulated in this study. Motion resistance contributed from cladding in a particular mid-rise building, a 19-story office building in downtown Los Angeles, is investigated. Analyses of clad models and unclad models are carried out, and clad models are discovered to displace less than unclad models. Therefore, cladding is able to contribute lateral motion resistance to a building during an earthquake, and structural engineers should include cladding in their analysis models when designing a building.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

Acknowledgements

I take this opportunity to thank the Department of Civil and Environmental Engineering for making this year an unforgettable experience of my life.

I thank Professor Jerome Connor for his support and advice throughout this academic year. He is one delightful professor who has a special way of teaching that makes all his classes entertaining.

I thank Lisa O'Donnell for her contribution to the MEng project throughout the year. Without her, our project report would not be as comprehensive and well organized. I also thank Simon Laflamme for his continuous support on my thesis, MEng project, and homework.

Finally, MEng Class of 2009 makes this year of my life so special and exciting. I thank all of you who assisted me and supported me throughout this year.

To my mom and dad, I am the luckiest person on earth to be your daughter. Thank you for your support and love. I love you.

Table of Contents

List of Figures

List of Tables

1. Introduction

Cladding has been considered as an aesthetic feature or architectural manifestation in a building and has been treated as a non-structural element. From an architectural perspective, cladding provides an important visual component for the building façade. Different cladding materials display different architectural perceptions and also serve different purposes for a building. For example, masonry cladding is able to store heat during the day and radiate warmth to the interior at night. Non-structural elements are usually not considered to contribute any stiffness to the building and do not require much attention in the design analysis. Hence, structural engineers pass the decision of the cladding material and connection onto either the architect or the steel manufacturer. However, cladding does affect the behavior of a building in an earthquake and does contribute significant drift control to the building motion. When structural engineers design buildings under seismic loading, they typically disregard the impact of cladding on the structure.

A number of studies have shown that cladding panels can help to control wind and earthquake motion of the buildings and should be treated as structural elements. Commonly, cladding panels and cladding connections are not explicitly modeled in building analyses. For design purposes, structural engineers remove cladding in the model and simulate these cladding weights at the bearing connections, which are designed to distribute the downward gravity loads. Therefore, the associated strength and stiffness contributed by the cladding panels and the connections are being neglected in the analysis model. Many structural engineers consider this unclad model as a more conservative assumption since the calculated story drift from an unclad model is larger than the actual drift from a clad model (Goodno & Palsson, 1986). If we compare these two models, the periods of vibration of the unclad model are larger. The increase in periods of vibration due to the additional cladding weights with no associated stiffness results in a decrease in the base design demand. These misdiagnoses will, therefore, influence the ground-motion demand and the building capacities.

The principle objective of this study is to investigate the role that cladding can play in the seismic response of mid-rise buildings in earthquake-prone regions. Advantages and disadvantages of using different cladding materials, systems, and connections on a building are reviewed in the beginning section of this thesis. The summary of the Northridge Earthquake, the ground motion input in this study, is provided in Section 3. The design and the model setup of the building simulation are presented in the following section. The results of the building drift in an unclad model and a clad model are examined in Section 5. Section 5 also specifies the level of drift control contributing by different connection properties and different directions of seismic load. The ultimate goal is to substantiate the claim that cladding panels can provide drift control to a mid-rise building during an earthquake. Section 6 gives the conclusion and summary of this study.

2. Cladding Design

The exterior component of the building envelope is considered to protect the occupants from precipitation, wind penetration and temperature fluctuation. Engineers are mainly concerned about its ability to resist severe weather, freeze and thaw effects in cold climate, and high temperature fluctuation. The design of the cladding panels determines the architectural feature and the thermal effectiveness of a building. The greatest benefit of cladding is its provision for light and views. However, studies have shown that even though cladding is not structurally designed to contribute stiffness to a building, it is proven to reduce building displacement under high seismic load (Bassler, 1992). The design of cladding must accommodate the deformation of the structural frame of a building to avoid stress accumulation in the cladding panel or the cladding connection. Different designs of cladding materials, cladding systems and cladding connections are studied in this thesis to thoroughly examine the feasibilities, advantages, and disadvantages of each design.

2.1 Cladding Materials

Materials that are commonly used in cladding are studied in this section. Different cladding materials have different esthetic manifestations and thermal functions on a building. The six main categories of cladding materials are introduced in this section: concrete, stone, masonry, metal, glass and plastic.

2.1.1 Concrete Material

Background

Concrete is mainly composed of cement, water and aggregates, which range in size from sand, gravel, and slag to lightweight minerals. Reinforcements such as wire meshes, steel bars, or even fibers are added to the concrete panel to increase its shear strength and tensile strength because concrete ages over time due to temperature fluctuation and shrinkage (Hunt, 1958). The concrete panel is categorized as placement cladding, which is sorted into precast panels and cast-in-place panels (Bassler, 1992). The precast concrete panel is more commonly seen on the building skin than the cast-in-place concrete panel.

Tensile strength in concrete is relatively low compared to its compressive strength. When engineers design the concrete panels, they intend to minimize the tensile stress that might develop in the structural framing system. However, when unexpected tensile stress occurs, the reinforcements inside the concrete panel will carry the tensile loads. Unexpected tensile stress can be flexure, diagonal tension, or differential strain that develops from lateral loading, concrete aging, temperature fluctuation, or concrete shrinkage. Moreover, high tensile stress will cause crack formations in the concrete panel and will reduce the durability of the concrete panel (Bassler, 1992). Hence, designers should consider this issue when selecting connections and reinforcements for the precast concrete panel.

The design process of the precast concrete panel involves selecting the exterior appearance, analyzing the handling and erecting loads, and determining the required concrete mixtures and reinforcements (Bassler, 1992). The connection of a cladding panel must be carefully detailed to ensure that the cladding will not fail before reaching its capacity. The responsibility of designing a precast concrete panel is shared among engineers, architects and precasters. Engineers are responsible for analyzing the in-service loads on the cladding panels, while the precasters are responsible of examining the process of handling and erecting the panels. However, the appearance of the precast concrete panels lies in the hands of the architects, who decide the texture and the color of the panels.

Although precast concrete panels were prevalent in the 1960s and 1970s, the construction industry has shown a gradual decline in the use of concrete panels in the recent years (Brookes, 1998). Lightweight cladding materials, such as glass and metal, have slowly replaced heavy concrete cladding because they can provide better architectural features and textures for the current trends in the architectural industry. Moreover, the lack of development in the textures and colors of concrete reduce the demand from the architectural industry (Brookes, 1998).

Advantages

The main advantage of using concrete as the cladding material is its resistance to fire since concrete is a non-combustible material (Brookes, 1998). Other advantages of using precast concrete panels include fast erection, freedom from shuttering support on the job site, and good insulating qualities (Brookes, 1998). Concrete panels can be shaped into different forms and sizes, and the materials for manufacturing concrete panels are readily available and easy to obtain (Hunt, 1958). Moreover, the fabrication and erection processes of concrete panels are simple to perform. Most importantly, precast concrete panels require only medium to low maintenance compared to the other cladding materials.

Disadvantages

One of the disadvantages of concrete is that its components are much heavier and thicker than those in the other materials. Hence, precast concrete panels impose more dead load on the building façade that structural engineers need to consider when designing the building. Moreover, concrete has a tendency to crack due to aging and shrinkage and to fail due to freezing and thawing (Hunt, 1958).

Limitation

The size of a precast concrete panel has an effect on the manufacture process, transportation method, and equipment management. One of the limitations of using precast concrete panels on a building façade is transporting them onto the job site. During transit, if a concrete panel is placed flat on a trailer, the width of the panel is strictly limited by the payload restriction (Brookes, 1998). Widths from 4 feet to 10 feet are the most reasonable and economical range for delivering the precast concrete panels to the job site. Police permission is needed for concrete panels that require the width of a delivery trailer to exceed 11.5 feet (Brookes, 1998).

Molds with standardized sizes are readily available in factories to create the concrete panels. For manufacturing purposes, the width of a concrete panel is limited to 4 feet, so the manufacturer can finish the panel surface efficiently (Figure 1). The standard thickness of a concrete panel is around 5 inches (Hunt, 1958). The typical thickness of the concrete panel verses the concrete panel length is illustrated in Table 1 below.

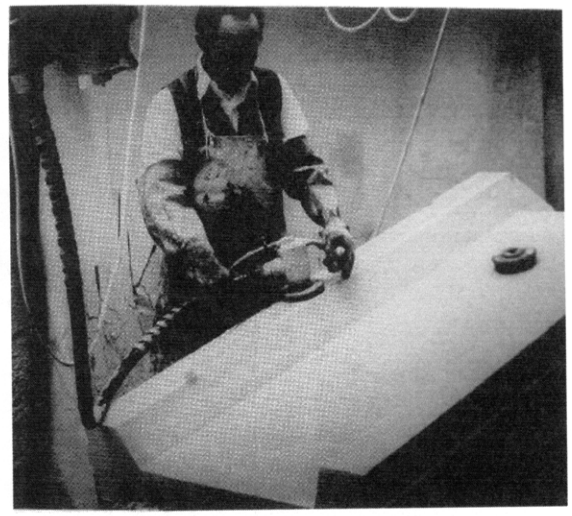


Figure 1: A worker finishing a cladding unit by hand (Brookes, 1998)

Table 1: Rule of thumb for panel thickness verses its length (Brookes, 1998)

Panel Length (ft)	Approximate Thickness (in)
6.6	3.0
9.8	3.5
13.1	3.9
18.0	4.9

Panel Fixing and Shape

Concrete panels can either be hung at the edge slab on a higher level or be supported at the base slab. They are attached to the edges of the slabs by either angle cleats or dowel bars (Figure 2). These cleats and bars must be detailed carefully to allow vertical displacement from cladding movements under seismic and wind loading. Cladding erectors have developed various shapes of concrete panels to reduce the cost of cladding installation (Chicago, 1990). Figure 3 below illustrates different shapes of precast concrete panels that are commonly employed in

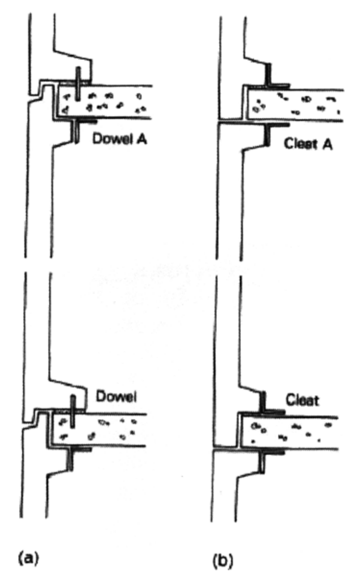


Figure 2: Different combinations of dowel and cleat panel fixings: (a) dowels top and bottom (b) cleats top and bottom (Brookes, 1998)

the construction industry. L and T shapes are the most common configurations chosen by architects and engineers because the number of costly joints is greatly reduced compared to that in the other shapes (Chicago, 1990).

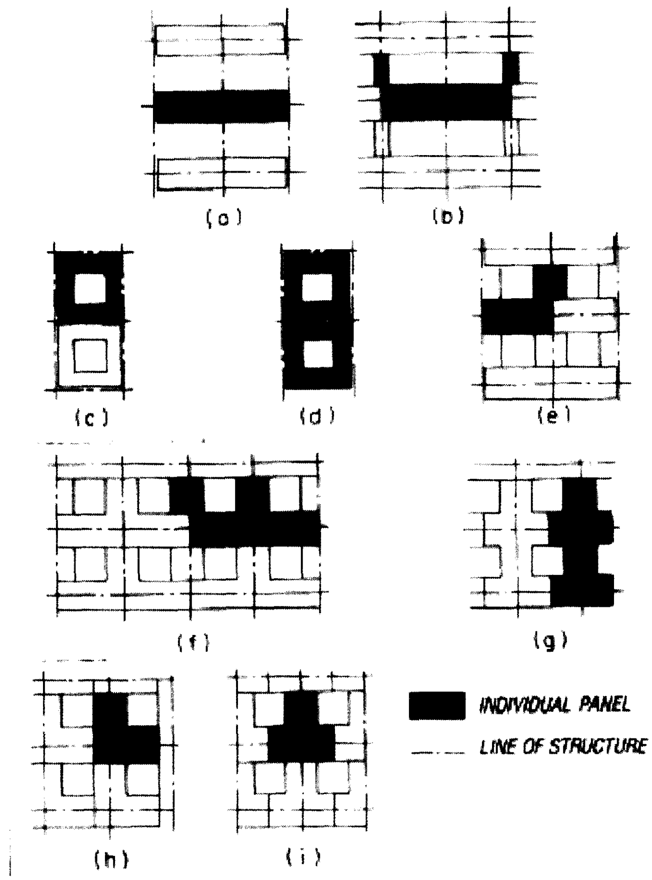


Figure 3: Different arrangements of precast concrete panels (Chicago, 1990)

2.1.2 Masonry Material

Background

In previous centuries, masonry cladding was commonly selected as the building façade (Figure 4). According to Bassler (1992), buildings were erected with thick and heavy masonry cladding façades such as massive load-bearing walls. Recently, designers have been developing thinner masonry cladding units to reduce the façade weight, but their knowledge of masonry properties is limited in thick masonry units. Moreover, the connection details and panel dimensions should be carefully designed because the weatherability of the masonry unit and the tensile strength in the bond between the mortar and the unit can cause the panel to crack and fail (Bassler, 1992). Masonry is not as adaptable to temperature change as the other cladding materials because an increase in temperature will cause significant volumetric change in the masonry unit (Bassler, 1992). Moreover, water can penetrate into the building through the gaps between the mortar and bricks. The gaps are developed due to water voids, bond separations or unit cracks. Exterior masonry installation must be cautiously constructed to avoid water penetration into the wall system (Weber, 2007). The stiffness of the masonry unit also should be carefully analyzed to avoid future crack and failure (Bassler, 1992).

Figure 4: Example of a building with brick cladding
(*Source: www. Heidelbergcement.com)*

Masonry cladding is categorized into two types: thin veneer and load-bearing walls. A load-bearing wall is represented by a massive, thick masonry façade. For many years, both architects and structural engineers have been pursuing lighter materials for building façades. Hence, the masonry bearing-wall has slowly been transformed into a thin masonry veneer, which is constructed mainly for the cladding feature.

Two types of masonry units are commonly seen on a building façade: masonry concrete and masonry brick. Figure 4 is a good example of a building clad with masonry brick façades. Although masonry concrete is actively supported by many manufacturers, high air content inside the masonry concrete unit greatly reduce the bond strength in the clay unit cladding (Bassler, 1992). The poor bond resulting from this high air content will produce a permeable cladding unit and will generate corrosion resulting from the water infiltration inside the cladding panels (Figure 5).

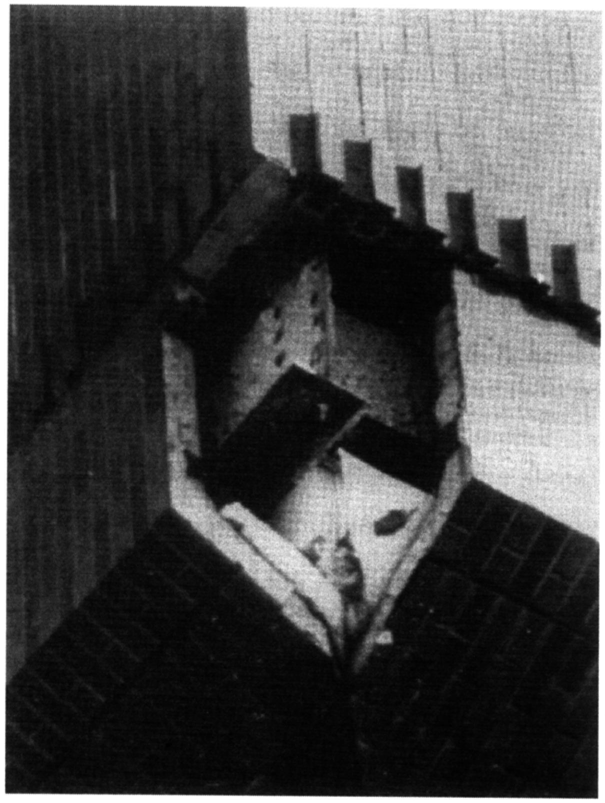


Figure 5: Cracking and failure in the masonry cladding caused by corrosion (Chicago, 1990)

System

Masonry veneer is composed of an exterior wythe of masonry units and an interior layer of a steel framed wall, which consists of waterproof sheathings and concrete masonry units (Weber, 2007). Masonry cladding prevents water penetration from entering the wall by having waterproof components installed into the system. Shown in Figure 6, the drainage cavity behind the exterior wythe provides a path for water that penetrates through the brick wall to leave the system. Weber (2007) recommends the minimum width of the drainage cavity to be 2 inches. All masonry façades should include holes or flashings to drain water that enters into the system (Bassler, 1992). Moreover, flashings should be carefully detailed to ensure water hindrance and to maintain the wall strength.

A flashing system is composed of a three-sided metal pan that collects water and provides a path for it to drain through the weep holes (Figure 6). Flashings must be designed with waterproof materials and installed properly near the corners, laps and terminations of the masonry units (Bassler, 1992). Stainless steel, copper, and lead-coated copper are commonly used as the flashing materials. These metals guide water to flow out of the system quickly and are also very durable in strength.

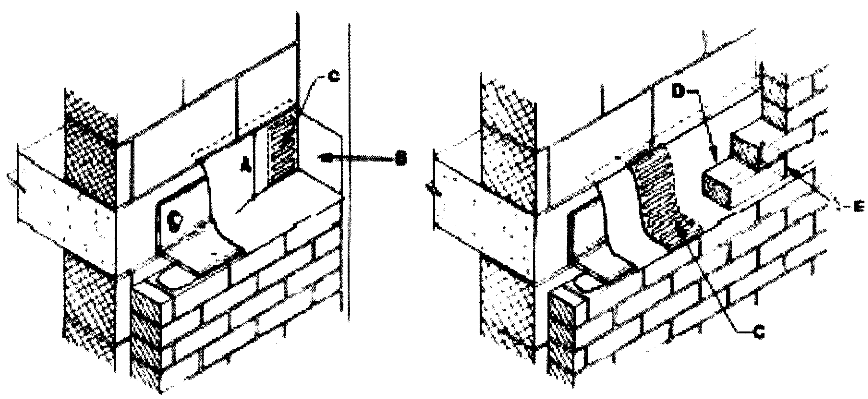


Figure 6: Flashing a masonry cladding cavity: A= adequate height (~8 in); B= end dams to contain water; C= sealed seams with mastic of sealant; D= clean cavity; E= weep holes to drain water at proper spacing (Bassler, 1992)

The following components are essential in a masonry unit (Weber, 2007):

- Drainage cavity behind a veneer wythe
- Flashing and weep hole system
- Seals for the cavity at fenestrations (near windows and doors)
- Lateral tie system to anchor veneer to the structural back-up
- Vertical support system to carry the veneer weight
- Clearance for the wall system to expand or contract

Advantages

The main advantage of using masonry cladding is its thermal performance throughout the year. Masonry cladding is able to store heat during the day and radiate warmth to the interior at night. It is able to absorb heat that is more than 100 degrees Fahrenheit (Weber, 2007). However, the wall cavity behind the masonry veneer provides most of the insulating work since the masonry unit itself provides little heat isolating value.

Masonry performs well in fire resistance and sound insulation because of its properties and thickness. To enhance the acoustic feature of the masonry unit, manufacturer will fill insulation barriers within the masonry veneer to eliminate the air voids inside the core (Weber, 2007).

If it is erected properly, masonry cladding does not require as much maintenance as the other cladding materials. Masonry units can have a service life of at least 100 years, depending on the material quality and connection detail. The sealant between the joints and the openings requires maintenance every 7 to 20 years depending on the usage wear and age. Based on the quality of the original installation, mortar joint should be refilled every 20 to 30 years (Weber, 2007).

2.1.3 Stone Material

Background

Since the rise of the tall building industry, stone cladding had remained popular until the late 19th century (Hunt, 1958). Stone is the oldest cladding material that remains throughout the history and recently regains its popularity on the mid-rise buildings (Bassler, 1992). Unlike the other cladding materials, stone has unique texture and color and is commonly seen on monumental and historical buildings (Hunt, 1958). An example of a building erected with stone cladding is shown in Figure 7.

Marble, granite and limestone are the most commonly used material for stone cladding. A stone unit is composed of either large stones or small stones that assemble into a composite element. Different support systems for stones are employed in the industry. Thick stones are usually anchored at the shelf angles or the angle clips, whereas thin stones are supported with the stone liners attached, resting on the angles or clips. However, liners must be carefully positioned to provide an adequate bearing capacity (Bassler, 1992). Unexpected stress can develop inside the stone veneer or in between the veneer and the structural frame, so the engineers must size the stones and detail the expansion joints properly to allow free space for the stone veneer to contract or expand (Bassler, 1992).

Figure 7: Typical appearance of a stone cladding (Hunt, 1958)

Advantages

Stone material has a long life expectancy although it also depends on the quality of the composition. The high quality controlled marbles and granites can last for centuries without significant wears (Hunt, 1958). However, some types of stone such as soft and weak sandstones deteriorate easily in a 10 year period. The service life of the stone cladding depends on its hardness, density and rate of water absorption (Hunt, 1958). Same as concrete and masonry, stone is also fire and corrosion resistant. Moreover, it has variety of textures and colors that produce amazing patterns and surfaces on the building façade. Oftentimes, architects favor stone as the cladding material when designing a monumental building.

Limitations

Two of the biggest concerns of using stone as the cladding material are its cost and weight. The weight of stone cladding has always been an issue in analyzing the loads on the structural frame and minimizing the construction cost (Chicago, 1990). An increase in the construction cost has encouraged designers to reduce the thickness of the stone veneer and the dead weight contributing from the stone cladding. However, the thickness of the veneer cannot be too thin, or the strength will be compromised and failure may occur. Bassler (1992) suggests the thickness of the stone veneer to be at least 2-inches to prevent future failure of the stone cladding. Insufficient understanding and analysis of the thin veneer may result in stress concentration and joint dislocations that will lead to cladding distress and failure (Chicago, 1990).

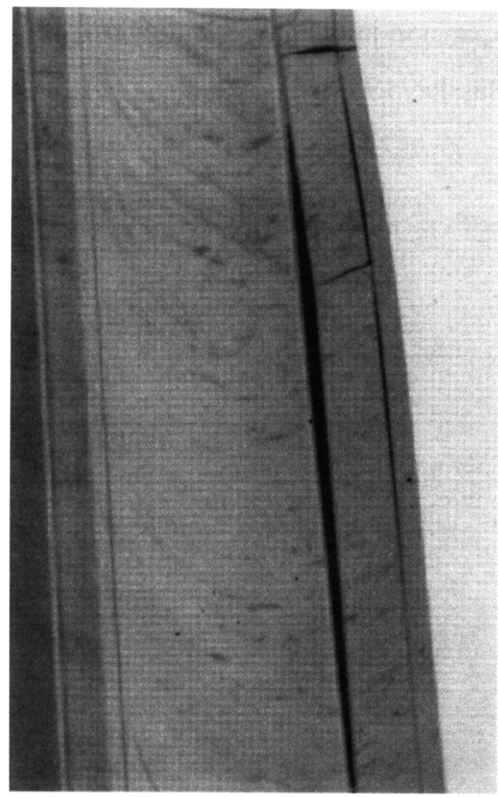


Figure 8: Stone bowing (Chicago, 1990)

Figure 8 shows the most common failure of stone cladding in high-rise buildings. Stone bowing is a result of volumetric change in the stone cladding when the stone veneer is subjected to constant temperature change and frequent moisture contact. The designers should pay particular attention to its properties because thin veneer has difficulty in resisting the expansion between the unexposed and exposed surface (Chicago, 1990).

2.1.4 Metal Material

Background

The metal cladding had its first recorded use on the building façade in the 1860s in the New York City (Bassler, 1992). The most commonly seen materials of metal cladding are aluminum and stainless steel. Metal cladding is categorized into plate, laminated sheet and sandwich panels. The laminated sheet panel is manufactured by compressing the metal sheets against a thin solid core with an inner metal liner (Bassler, 1992).The thin solid core can be made out of plywood, hardboard, particle board, gypsum board, cement board, or thermoplastic. The sandwich panel is manufactured by hot-pressure laminating a rigid foamed insulation or a nonsolid core between two metal sheathings. The nonsolid core can be either paper or metal honeycomb. If the bond inside the sandwich panel is not strong enough or the adhering process is not properly handled, delamination in the sandwich panel may occur due to frequent moisture contact.

Metal cladding either forms a pattern of a grid frame or back-fastens an interior girt frame system on the building façade (Bassler, 1992). Manufacturers have different methods in handling and erecting the metal cladding onto the building. Some manufacturers provide the grid or the girt frame as a whole complete cladding system, while others manufacture cladding in panels and attach them onto the structural frame at the job site (Bassler, 1992).

The most commonly used metals in the cladding construction today are aluminum and stainless steel. In the next section, the advantages and disadvantages of using the aluminum and the stainless steel are reviewed.

Aluminum vs. Stainless Steel

Aluminum

Compared with steel, aluminum is excellent in absorbing dynamic load. With the same deflection, aluminum can absorb eight times more loading than that in steel. However, aluminum yields at an earlier time than steel. The natural appearance of aluminum alloys is gray, but it can be processed into different textures, degree of brightness, degree of reflectivity and colors (Figure 9).

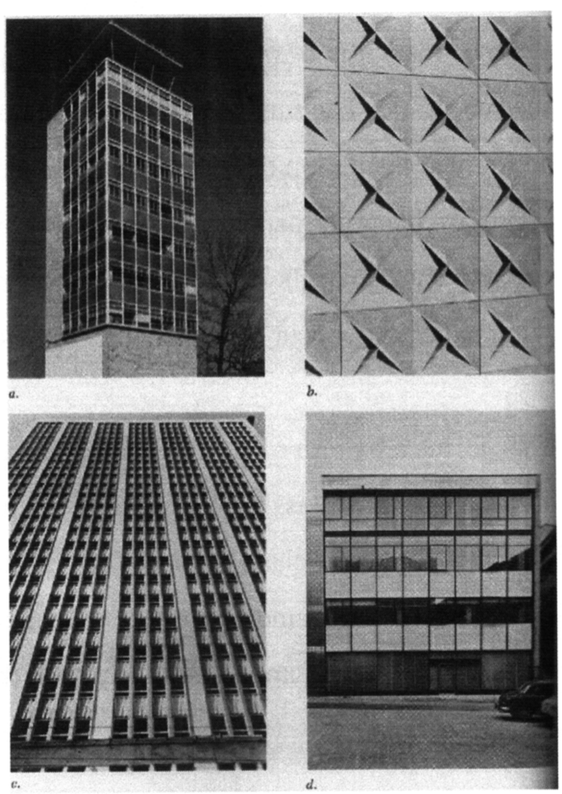


Figure 9: Various appearances of aluminum alloys cladding panels (Hunt, 1958)

Advantages

Light in weight, aluminum cladding has fewer joints than the other heavy cladding panels and allows easy fabrication and erection process. It can be generated into a variety of appearance with different form, texture, finish and color. Moreover, aluminum cladding has high corrosion resistance, high strength-to-weight ratio, and high weather resistance (Hunt, 1958). Most importantly, it is easy to handle and erect compared to the other cladding materials. Oftentimes, owners and investors favor aluminum cladding more than the other materials because aluminum has high salvage value.

Disadvantages

Aluminum is expensive to fabricate if particular finish, color or texture is requested. The melting point of aluminum is fairly low compared to other materials; so fire resistance material is installed in the cladding to ensure that it will not fail spontaneously in the events of fire. Elevated temperature will cause the aluminum cladding to experience lower tensile strength, higher elongation and higher mechanical properties. Hence, on recommendations of the cladding experts, 3/8-inch clearance is required for every 10 ft of cladding length (Hunt, 1958).

Stainless Steel

Stainless steel has become one of the most commonly employed cladding materials because of its strength and corrosion resistance. Although the Modulus of Elasticity of the stainless steel is not as much as that of the structural steel, it is still in the range of 28,000 to 29,000 ksi. Strength of any grade of the steel cladding remains fairly high at low temperature and relatively high at high temperature compared to the other cladding materials. The life expectancy of stainless steel cladding depends on the steel grade and the manufacture quality. Stainless steel is famous for its durability and corrosion resistance, which requires constant maintenance to keep the steel surface clean and continuous oxidation process in the cladding.

Advantages

The natural color of the stainless steel is gray, but it can be adjusted through manufacturer process (Figure 10). Moreover, stainless steel can be molded into different shapes, including pipe, tubing, strip sheet, and plate (Hunt, 1958). It is relatively flat compared to the other materials and is resistant to abrasion and wear. Its weather and thermal resistance will help it to survive in harsh climate. Moreover, stainless steel can be easily cleaned by washing it merely with water and soap.

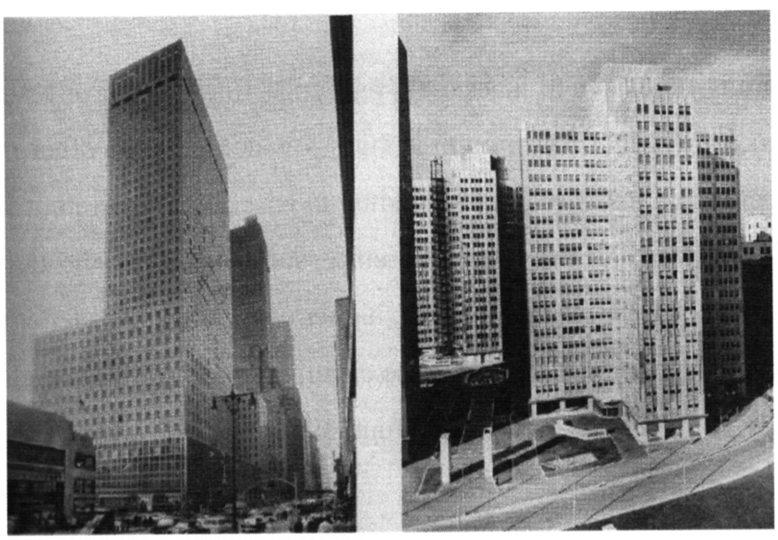


Figure 10: Texture and appearance of stainless steel cladding (Hunt, 1958)

Disadvantages

One disadvantage of the stainless steel is the cost of material; steel is expensive compared to the other cladding materials. Also, although it can be handled and erected by various methods, stainless steel requires a lot of manpower and time to fabricate and install (Hunt, 1958).

2.1.5 Glass Material

Background

Most of the modern architects favor glass as the material of the building façades (Chicago, 1990). Many modern architects desire sustainable features in the building such as natural daylight and maximum views. Moreover, architects can play around with different combinations of the glass properties until the perfect finish is achieved. Figure 11 presents different finishes of the building skin, and they provide different personality for the building. The color of a glass curtain wall can be clear, tinted gray, bronze, green, and blue (Chicago, 1990). Transparency of the glass is ranged from fully opaque to fully transparent. The glass cladding can either be uncoated or coated. Uniformed, metallic or patterned are the coatings that the architects or owners can select. Moreover, the architects or the building designers can choose the glass façade from glass that is annealed, heat-strengthened or tempered (Chicago, 1990). A different combination of the above characteristics will provide different textures and personalities for the building façade.

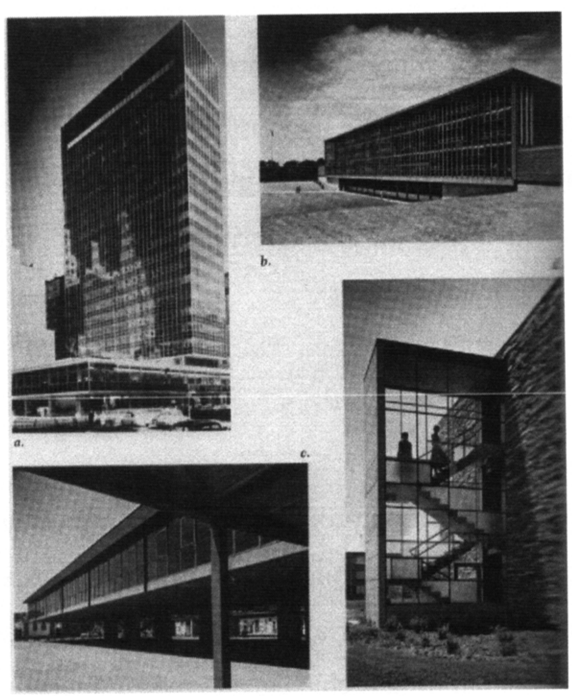


Figure 11: Various appearances of glass cladding panels (Hunt, 1958)

Nowadays, glass curtain wall has been increasingly employed on the building skin of the high-rise buildings. The main reason of using glass cladding on the high-rise buildings is that glass is light in weight. The cladding system of glass is comprised of a glass unit inserted into the aluminum framework, which is attached to the structural frame with aluminum vertical-mullions and horizontal rails (Chicago, 1990).

Limitations

The most common problem of the glass curtain wall is water leakage, which can attribute to the cladding failure. According to Chicago Committees on High-Rise Buildings (1990), tempered glass windows have spontaneous breakage that can be difficult to prevent. Therefore, tempered glass is not an option for most of the façade designers unless the properties of the glass meet all the safety and strength requirements.

Unlike the other cladding materials, glass is installed in a curtain-wall frame. A 2 four-sided structural sealant glazed system is the most popular glass curtain-wall system. Nonetheless, this system requires special attention to the adhesive properties of the sealant between the glass and the framework. Poor quality of the sealant and lack of quality control on the installation process may result in serious water leakage. Most of the glass curtain-walls today employ multiple-pane insulating glass, which is manufactured by 2 to 3 sheets of glass with sealed air in between the sheets to prevent moisture accumulation (Bassler, 1992).

Design

While meeting the specification provided by the architects and the engineers, the manufacturers also need to select the framing, seals and gaskets carefully. The manufacture engineers are responsible for all elements in the glass curtain-wall system to meet the criteria given by the building architects and the engineers. The manufacture engineers should pay attention to problems such as sizing of the structural connection, water penetration, air leakage, thermal resistance, lighting, acoustic performance, fire resistance, and thermal expansion (Bassler, 1992). The building designers should consider different options of glass and glazing in order to provide a design that meets both safety and esthetic standard. The designer should evaluate the potential of glass breakage resulting from heat gain and heat loss, lateral load resisting requirement, hazard potential from glass breakage, and fire resistance (Bassler, 1992).

Advantages

Transparency of a glass unit can be adjusted in a range from fully translucent to fully opaque. Architects can select the transparency based on the request from the owner for privacy and natural sunlight. Other advantages of glass material include its incombustibility, low heat conductivity, resistant to abrasion, and high strength under constant pressure.

Disadvantages

Under severe impact, glass breaks easily; therefore, designers should consider the frangibility of the glass as it can encounter lateral loadings such as wind and earthquake excitations. Glass also expands significantly under high temperature, and it breaks easily in tension under thermal expansion. The cost of glass curtain-walls can be expensive if special glass texture or finish, such as multiple glazing or heat-absorbing glass, is requested.

2.1.6 Plastic Material

Background

Before plastic was introduced as a cladding material, it had always been a secondary role in the cladding system such as adhesive or sealant (Hunt, 1958). Recently, plastic curtain-wall has been employed, and it has now been used frequently to produce an artistic modern façade (Figure 12). However, no scientific theory or definition has developed or enforced on plastic. It falls in the category of either sheet plastic or polymer modifier (Bassler, 1992). Plastic can replace glass or metal siding in providing a more dramatic expression on the building skin. It can be clear, plain polycarbonate, textured, or colored. Because of its flexibility in the plastic formulation, plastic is able to imitate the texture and personality of the other cladding materials. The designers had to spend a significant amount of time and money on a carved stone unit. Yet, they do not need to spend as much effort if the plastic is used to imitate the shape of the carved stone unit (Bassler, 1992). The development of reinforcing meshes and hard-coat systems has been accomplished by the manufacturers. The reinforcements will increase the resistance of the plastic cladding when encountering impact or lateral forces. Although plastic cladding has not been tested adequately over the past, it shows potential in the future development in minimizing the construction cost (Bassler, 1992).

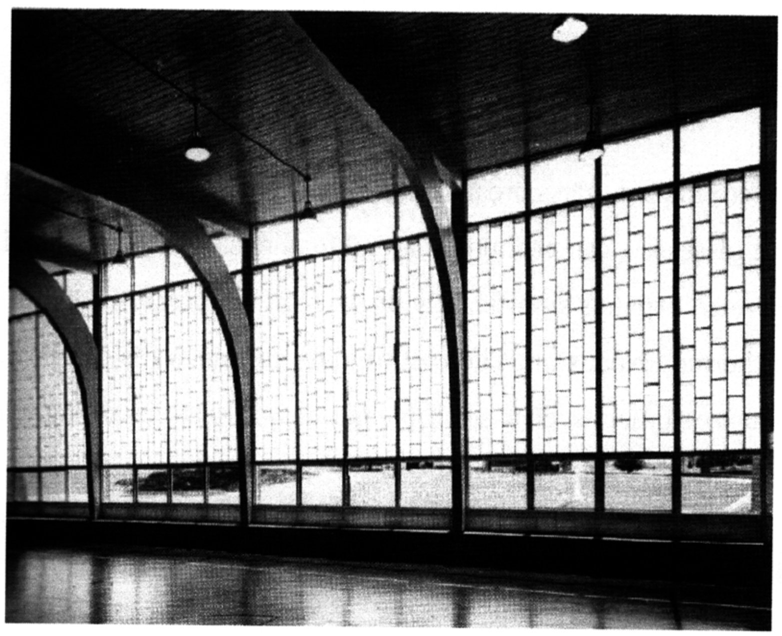


Figure 12: Appearance of a typical glass curtain wall
(Hunt, 1958)

Before plastic became available as a cladding material, glass was the only material that can provide different transparency for the building façade (Hunt, 1958). Now that the plastic curtain wall is readily available, it can supply light transmission and optical qualities to a building at a cost lower than that for the glass. However, the transparency of the glass material depends on the quality of the material as well. Some plastic material has low translucency while the others can provide full translucency. Hence, the architect should select the plastic properties based on the request and the budget from the owner.

Plastic is not as resistant to abrasion as glass, so it turns cloudy after scratched by dust, leaves or trash. Under high temperature, plastic tends to expand significantly; therefore, designers must consider allowance for the plastic unit to expand. Unlike glass, plastic is very resistant to breakage and shattering.

Advantages

Plastic can be processed to almost unlimited number of colors. It has a wide range of transparency from fully opaque to fully translucent. Different combinations of color, transparency, quality and finishing surface will provide different textures and personalities for the building. Moreover, plastic is very light in weight and low in thermal conductivity (Hunt, 1958).

Disadvantages

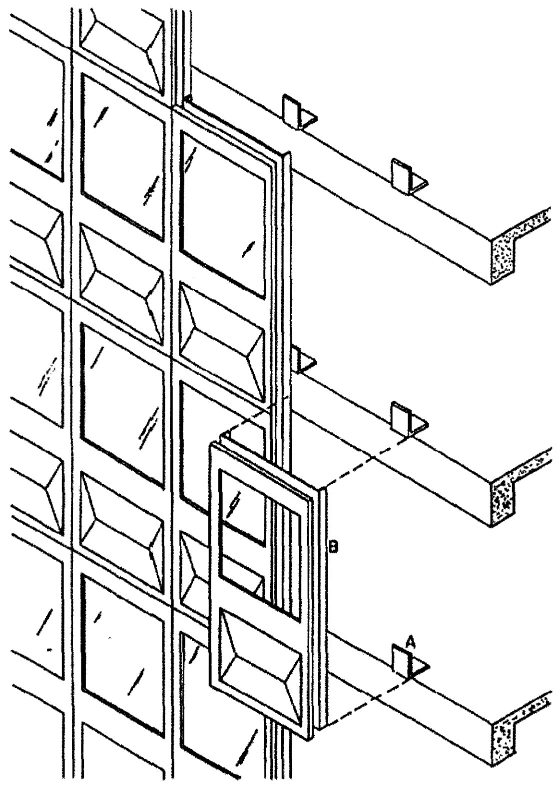
Under high temperature, plastic will expand significantly, resulting in great stress in the connections and the panels; failure will occur if too much tension is developed. Moreover, plastic has poor elastic behavior that creeps occur easily and has relatively low stiffness compared to the other cladding materials (Hunt, 1958).

2.2 Cladding Systems

In order to design the most effective cladding, not only does the cladding material have to be carefully selected, but the cladding system should also be cautiously examined. The material and system should be studied together to determine the most appropriate method for fabricating, assembling, transporting, hoisting, and installing (Chicago, 1990). Three basic cladding systems are evaluated in this section: the attached system, curtain-wall system and infill system.

2.2.1 Attached System

The attached system has large panels that attach directly to the structural frame of a building spanning one or more stories or one or more bays. Precast concrete and steel-stud frames with exterior finishes are usually erected in place using the attached system. Panels are lifted in place by a crane and fixed onto the anchorage, which is already fastened at the edge of the slab at the time of panel installation. Illustrated in Figure 13, a brick veneer wall is lifted in place and supported by shelf angles, which are constructed at the edge of the slab.



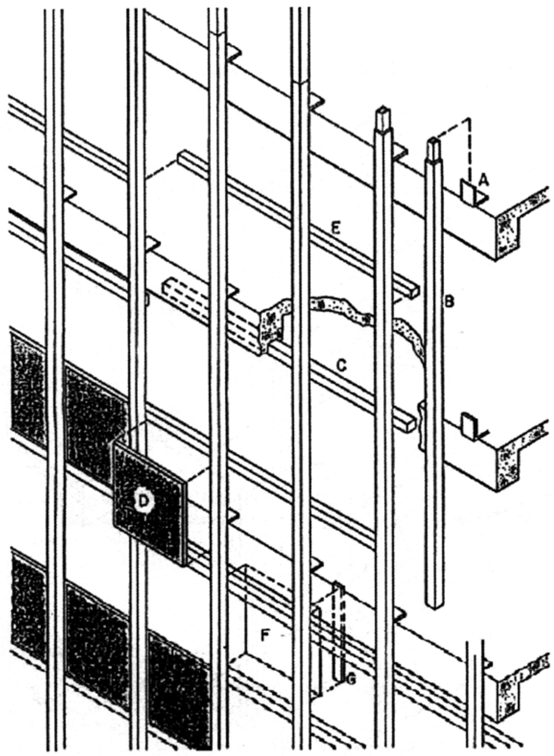
Attached systems: A = anchor; B = attached panel.

Figure 13: Attached System (Bassler, 1992)

The advantage of using the attached system is that it helps to eliminate the on-site construction time and reduce the difficulty of the construction. The time is mostly spent on delivering these prefabricated panels to the site and on assembling them on the job site. However, the disadvantage is that the time needed for design, shop drawing approval and manufacturing of these panels may exceed the reduced construction time. The design for this system must be carefully examined to avoid future problems such as water leakage and material deterioration due to weather.

2.2.2 Curtain-Wall System

The curtain-wall system is similar to the attached system, except that the panels are attached to the structural frames with clip angles and not to the slab edges with anchors (Figure 14). The most commonly seen cladding panels used in this system are metal and glass, but precast lightweight panels are also sometimes used in this system.



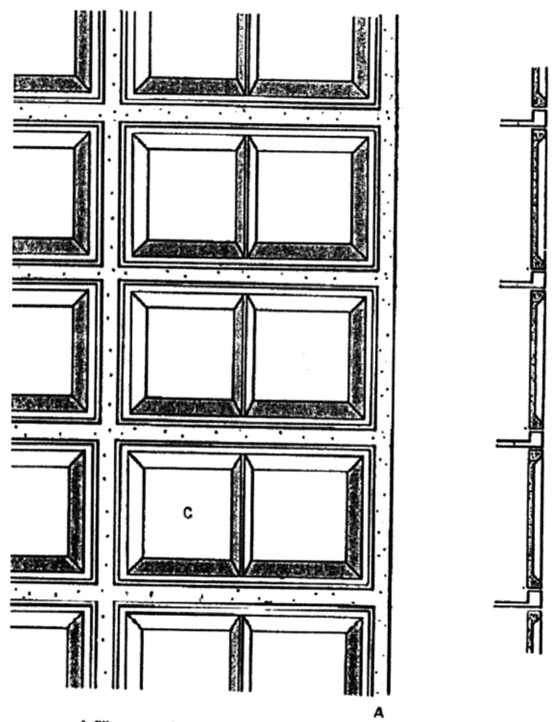
Curtain-wall systems: A = anchor; B = mullion; C = cast-in-place rail; D = spandrel panel; E = horizontal rail; F = vision glass; G = interior trim.

Figure 14: Curtain-Wall System (Bassler, 1992)

The advantage of using this system is the ease of construction since the material being used is usually light and does not require special expertise for handle and assembly. Moreover, this material-system combination is standard in design and manufacture. Therefore, the time required for shop drawing approval and manufacture is not as lengthy as that of the attached system (Bassler, 1992). The manufacturers design the joints and connections based on their knowledge of the material, system and structural frame properties provided by the architect and structural engineers. Materials that are not light in weight should have their joints and connections carefully analyzed to prevent future structural problems caused by different building movements.

2.2.3 Infill System

The infill system is easy to recognize because the structural frame is exposed. As indicated in Figure 15, cladding panels are installed between the columns of the structural frame spanning from one to another level of the slab. The cladding material that is most commonly used in this system is the cast-in-place concrete panel. Other materials that can be effectively installed in this system are precast concrete, masonry, glass and glass (Bassler, 1992).



Infill systems: A = exposed column; B = exposed slab; C = infill panel.

Figure 15: Infill System (Bassler, 1992)

The main advantage of using this system is that the cladding panels can be installed from inside the building, reducing safety concerns about working on scaffolding. Nonetheless, this system has difficulty in insulating heat because the structural frames are exposed to the exterior causing significant heat loss and heat gain in the floor slabs. The fluctuation of temperature throughout the day causes the structural frame to expand and contract. The design, selection, and assembly must be carefully performed to avoid future structural problem such as fragmentized concrete. Moreover, designers must examine the behavior of the structural frame and the precast concrete panel because the structural elements will be loaded non-uniformly as they age (Bassler, 1992).

2.3 Cladding Connections

In addition to the design of the cladding material and cladding system, connection is another primary issue that engineers should analyze when designing the cladding. Different connection details will determine the cladding panel movements when a lateral force is applied. Connections are expected to be isolated from the structural frame, so that the building façade can move independently from the structural frame during an earthquake. The connections in the cladding panels must provide enough freedom of the in-plane movements for the panels. The seriousness of the damaged cladding panels depends on how well the panels are connected to the buildings. Connections have been studied to contribute stiffness to a building in the transverse direction. Figure 16 shows two different connections of cladding that are employed in the industry: Lateral Stayed Connection and Rocking Connection. Figure 17 displays the mechanism of the story drift accommodation from each connection.

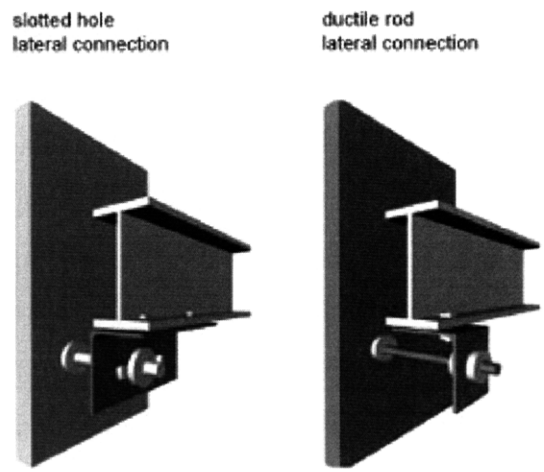


Figure 16: Example of rocking connection (left) and lateral stayed connection (right). (Arnold, 2008)

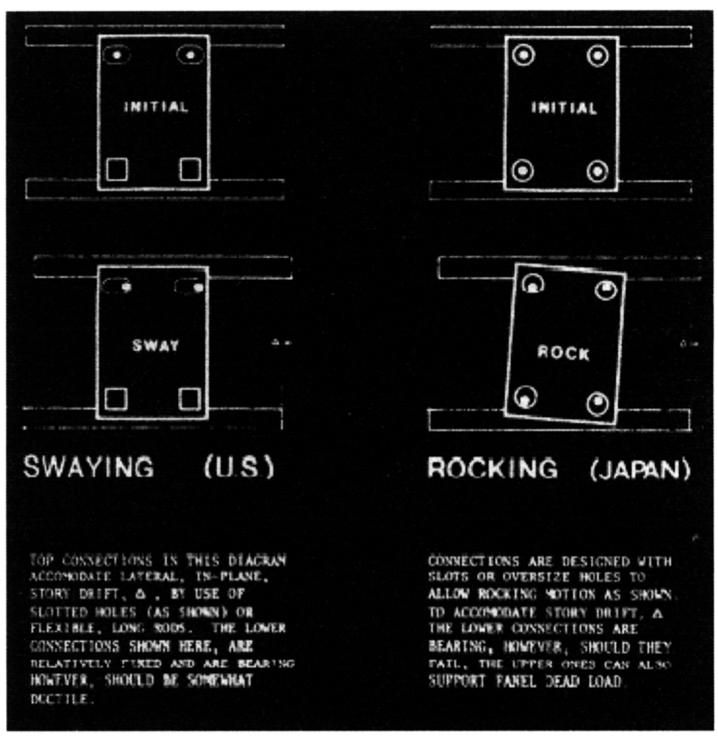


Figure 17: Mechanisms to accommodate story drift (Bassler, 1992)

2.3.1 Lateral Stayed Connection

Relying on the translational motion of the cladding panel, the lateral stayed connection accommodates the building frame movement during an earthquake. The bottom level connection is the bearing connection, which supports the weight of the panel and carries in-plane shear. The bearing connection is relatively fixed compared to the lateral connection. The top level is the tie-back or the lateral connection that allows lateral, in-plane story drift. However, the bearing connection can be installed either at the top or at the bottom level. Both locations have advantages and disadvantages regarding the movement of the structural frame. As displayed in Figure 18, cladding panels are commonly designed with the lateral stayed connection at the top and the bearing connection at the bottom to avoid tension developing in the concrete panel due to the downward gravity force (Bassler, 1992). However, if the tie-back connection fails, the panel will rotate outward and will place significant amount of moment on the bearing connection. Hence, some engineers believe that the lateral stayed connection works better with the bearing connection supporting the cladding weight at the top in case the tie-back connection fails.

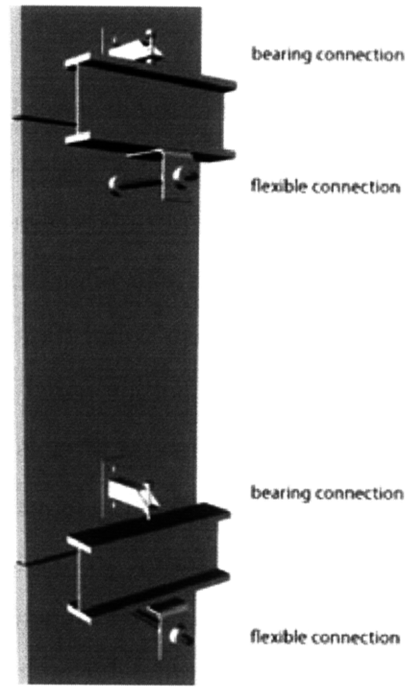


Figure 18: Typical lateral stayed connection that has bearing connection at the bottom and lateral connection on the top (Arnold, 2008)

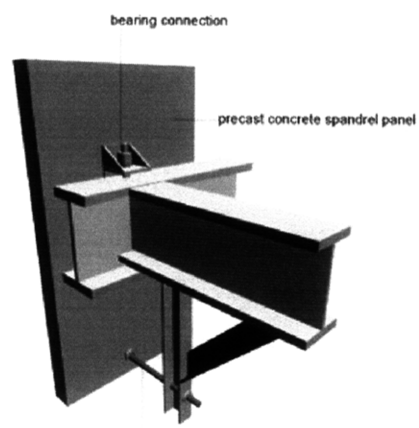


Figure 19: Deep spandrel panel with bearing connection at top and lateral connection at bottom (Arnold, 2008)

As shown in Figure 19, the engineers install the bearing connection at the top of the panel when designing a spandrel panel that spans from floor to floor. The story drift will not put too much impact on the lateral connection of the spandrel panels since the floor beams act together from floors to floors. The deep precast spandrel is attached to the steel beam with the bearing connection at the top and the lateral connection at the bottom. Hence, the glazing system will accommodate the interstory drift of the building.

2.3.2 Rocking Connection

The rocking connection or the sliding connection is designed with oversized slotted holes at the corners of the panel. In this mechanism, the connections are hinged at the corners of the panel to allow free rotation when the building drifts. The rocking connection has been tested to accommodate the interstory drift of a building in a moderate earthquake (Bassler, 1992). When the building drifts, the hinged connection allows many degrees of freedom in between the structural frame and the cladding panel. However, the rocking connection must be designed carefully to avoid the bolts from sticking inside the slotted hole. The sliding connection is not used in the high seismic zones because high seismic loading will cause jamming and binding in the connections and distortions of the structural frame when the connection is not detail adequately (Bassler, 1992).

3. Ground Motion Input: The Northridge Earthquake

On January 17, 1994, the Northridge Earthquake occurred and caused many heavy cladding panels on the building façade to fall off or hang at the perimeter of the structural frame. These cladding panels were considered as nonstructural elements and hence, they are not anticipated to participate in resisting the load on the building. Therefore, when designers analyzed the building, they did not model the cladding panels into the building model. Since these cladding panels can seriously impose danger to human life, investigation of these cladding panels as a subsystem in the three-dimensional framing structure is required.

3.1 Summary of the Northridge Earthquake

The Northridge Earthquake occurred in California at 4:31a.m; it took place in the early morning, so the number of injuries was minimized. During this earthquake, building collapsed partially, steel welded connections fractured, water and sprinkler pipes fragmentized, HVAC equipment was damaged, and suspended ceilings and lighting fell down (Cohen, 1995). Damaged cladding panels and connections were categorized as the less dramatic failure in this incident. Before the earthquake occurred, cladding was fixed to the outside skin of a building. During this incident, many heavy cladding panels on the wall of numerous residential and commercial buildings fell down to the ground; moreover, a few of them were left hanging at the perimeter of the structure frame.

The cladding panel acts as a protective and insulating barrier that controls weather infiltration. The Northridge Earthquake brought attention on the significance of cladding performance in seismic design. The failure of these panels was a result of insufficient understanding of the behavior of the panels in the seismic design and the connections as a subsystem in the three-dimensional framing system.

3.2 Cladding Failure in the Northridge Earthquake

The earthquake caused many heavy cladding panels to dislodge from the structural frame and some panels hanging unstably on the structural frame. These damaged cladding panels and connections were reported as the unanticipated failure in this incident. Cracks on the precast concrete panel, damaged connections, hanging concrete beam cover, and buckled metal cladding were reported in this incident (Cohen, 1995).

Buildings that were built within 2 years before the Northridge Earthquake had cracks on the precast concrete panels after the earthquake (Cohen, 1995). X-cracks formed on the panels when the earthquake occurred because these panels became part of the lateral-load resisting system. X shear cracking on the concrete panel is a common earthquake product on the building façade. The panels intereact with the structural frame of the building when the lateral motion occur and provide lateral stiffness to the building movement like a shear wall. The interstory drift resulted from the earthquake will induce significant stress on the panels when the panels are not isolated from the structural frame. Although cladding is intentionally to be isolated from the frame system, it will still contribute some degree of stiffness to the building. Section 4 focuses on the stiffness contribution by cladding with a building simulation in SAP2000.

4. Simulation: 19-Story Rectangular Office Building

A simulation of a 19-story tall office building located in Los Angles, California is analyzed in this thesis to investigate the stiffness contributed by cladding. Parameters and variables were chosen arbitrarily in this analysis. This building has a lateral load resisting system consisting of the moment frames at the edges of the longitudinal façade and x-bracings in the inner frames of the latitudinal façade. Barry Goodno and Hafsteinn Palsson (1984) had proven that precast concrete panels do affect the behavior and the response of a building during an earthquake. In this study, stainless steel with a grid framing system was chosen as the cladding material because the information about the actual building façade was difficult to obtain and metal cladding has become more prevalent nowadays than precast concrete. The influence of the steel cladding on the structural frame is carefully examined and analyzed in the sub-sections.

4.1 Design and Setup

This 19-story office tower is analyzed using SAP2000. The time-displacement history of the Northridge Earthquake is provided in Appendix B (courtesy of the University of California Berkeley).

The longitudinal direction of the building is defined as *x* axis, and the latitudinal direction of the building is defined as *y* axis. As shown in Figure 20, this office building has 9 bays in the *x* direction, and 3 bays in the *y* direction. Each bay contains 3 stainless steel cladding panels (Figure 20). The floor slab is assumed to be 6 inches in thickness and modeled as normal weight concrete with 4000 psi of strength. Since this study focuses on the exposed building envelope, the basement level is disregarded and the fixed supports are modeled as the ground restraints. The layout of the building is defined in Appendix A.

Design loads assumptions (load combination of 1.2D+1.6L per ASCE 7-05):

Floor

Dead Load (D):

Suspended ceiling and lights	5 psf
Mechanical and electrical	10 psf
Total:	15 psf

Live Load (Reducible per IBC 2006):

Total:	100 psf

Roof

Dead Load (L):

Suspended ceiling and lights	5 psf
Mechanical and electrical	10 psf
Insulation and water-proofing	20 psf
Total:	35 psf

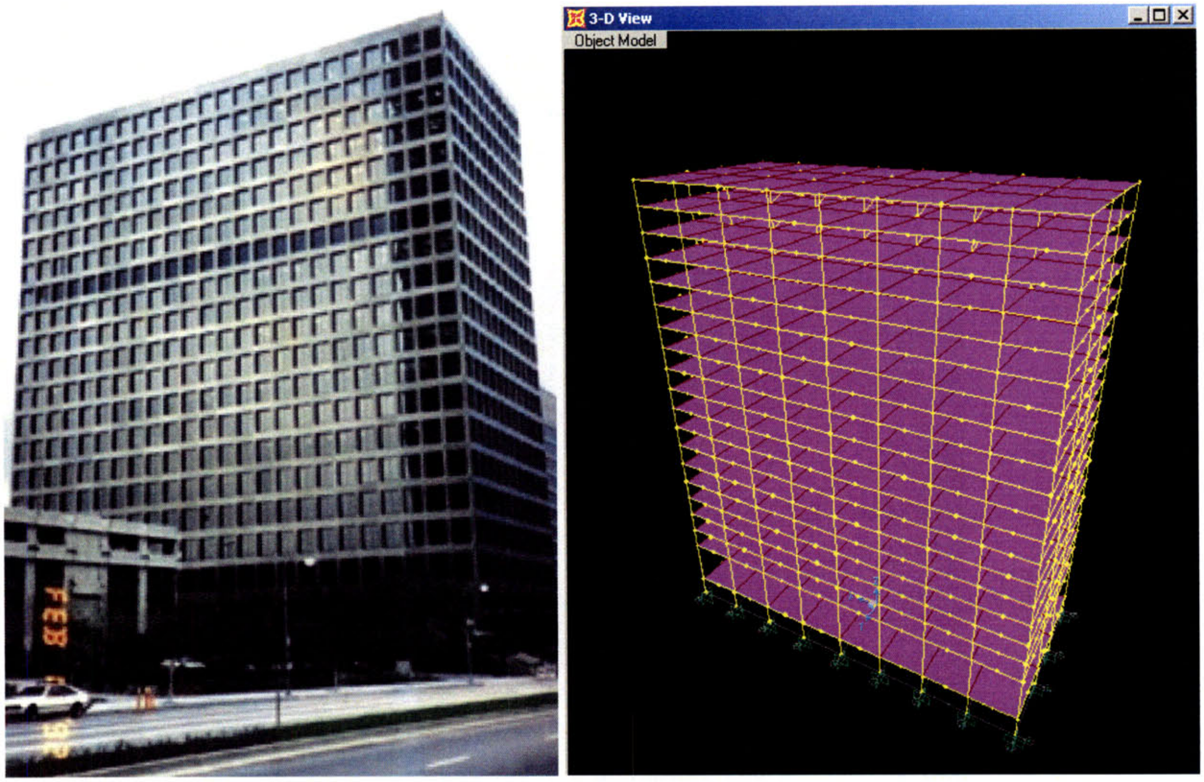


Figure 20: 19-story office building in Los Angles: Actual Building (left) SAP2000 Model (right) (CSMIP, 2007)

4.1.1 Unclad Model

Typically, for design purposes, structural engineers remove claddings in the model but simulate these cladding weights at the bearing connections, which are designed to distribute the downward gravity loads. However, the associated strength and stiffness contributed by the cladding panels and the connections are neglected in the analysis model. Hence, in this unclad model, the weight of all the cladding panels in the building is added the center point of each bay (Figure 21). The weight of each stainless steel cladding panel is estimated to be 35 psf (Cohen et al, 1992). In the *x* direction, the total cladding panels weigh 14 kips in one bay with an area of 13.3 feet in height and 30 feet in length. In the y direction, the edge bays span 40 feet, so the cladding panels weigh 18.7 kips in each of these bays. The second level has an intermediate floor that is 18 feet in height; the entire second floor is 30 feet in height. On the second level, the cladding panels weigh 31.5 kips in the x direction and 42 kips in the y direction. Figure 21 shows the dead weights contributed by the cladding panels, applying at the center point of each bay.

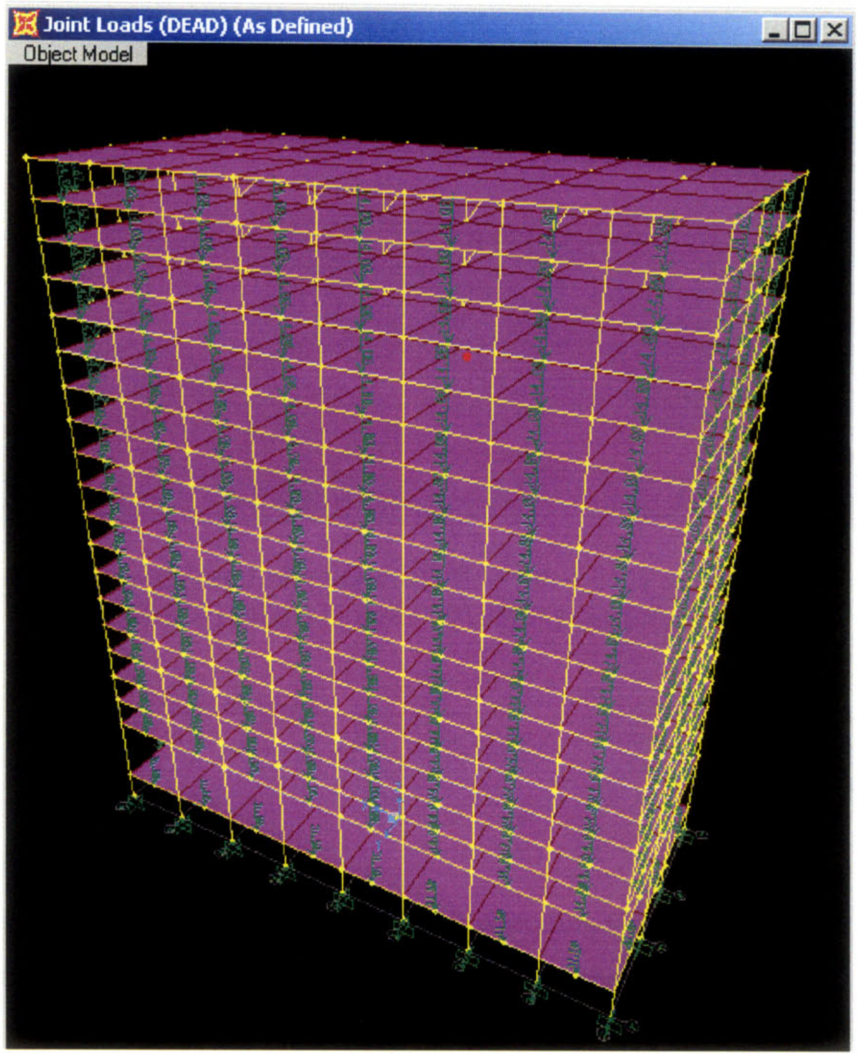


Figure 21: Unclad Model with added cladding weights

The sections of the frame members are auto-designed and checked in SAP2000. The size of the columns near the ground level is larger than the ones near the roof level because the columns near the ground level carry more axial forces. The bending moment increases as the elevation decreases because the lower level carries more bending contributed from the weights of the upper floors. Therefore, the bottom floors are designed to have bigger girder sections.

4.1.2 Clad Model

By keeping all the properties and member sections the same, the effect of the stainless steel cladding on the building is studied by comparing the displacements in the clad and unclad models. Steel cladding has stiffness in a range from 1,000 kips/in to $1x10^6$ kips/in (Cohen et al, 1992). If the modulus of the steel panel is assumed to be the same as the structural steel, moment of inertia of the cladding panel is calculated to be in a range of 11,770 in^4 to 11,770,000 in^4 using the equation below. Steel cladding is modeled in SAP2000 with the calculated properties defined in the frame section. The weight and the mass modifier are set to be zero since the dead weights of these panels are already added at the bearing connections in the building model.

$$K = \frac{12EI}{L^3}$$

E= Modulus of Elasticity

I = Moment of Inertia

L= Length of the Column

The cladding panels and connections are assumed to provide 100 percent resistance in stiffness. Hence, R_w, the overall strength and ductility factor associated to the lateral load resisting system, is 8 (Cohen et al, 1992). The dashed lines in Figure 22 represent the cladding panels that are added to the structural frame.

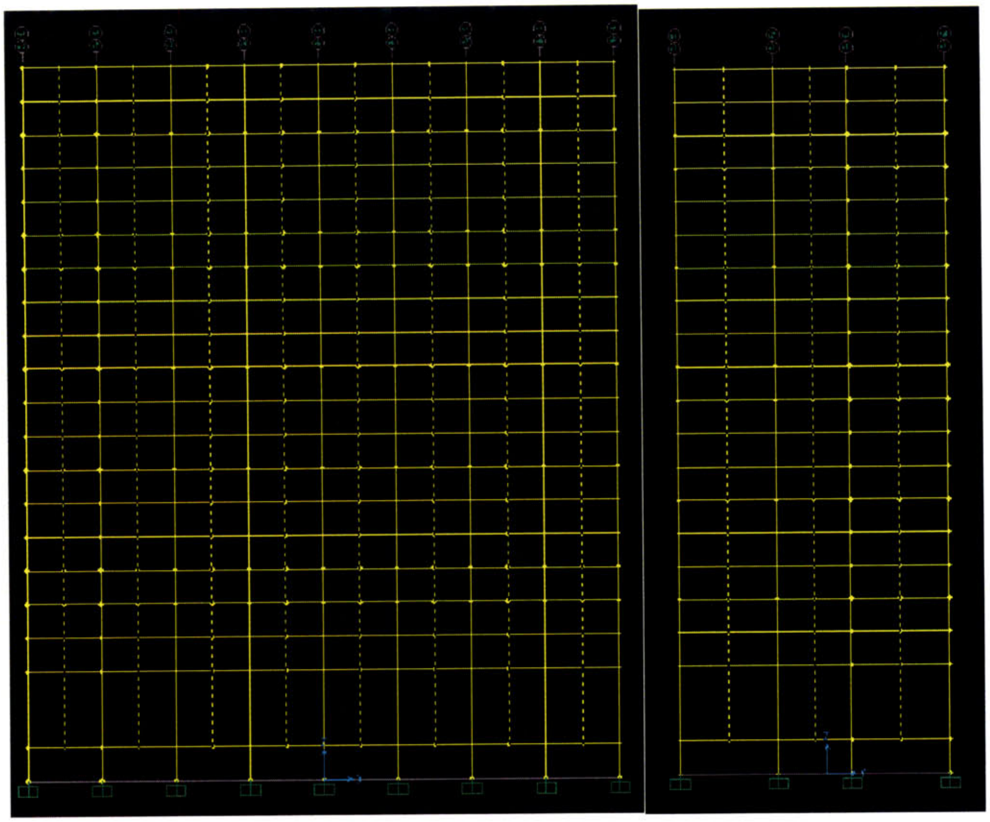


Figure 22: Cladding panels, represented in dashed lines, are added in the structural framing system, cladding in x direction (left), and cladding in y direction (right)

Lateral Stayed Connection

As discussed in Section 2.3.1, the lateral stayed connection is flexible in the transverse direction at the top level and relatively fixed at the bottom level. The lateral stayed connection is modeled in SAP2000 with the shear force in the major direction released at the top joints. When the building displaces under the seismic excitation, shear stress will develop in the cladding panels in the transverse direction to resist the building movement. The behaviors of the panels with the lateral stayed connections are discussed in Section 5.

Rocking Connection

As discussed in Section 2.3.2, the panel is free to rotate at both the top level and the bottom level. The rocking connection is modeled in SAP2000 with the moment released at all joints in the major direction. Under a seismic excitation, the slotted holes in the rocking connections will restrain the panels from rotating outward, and shear forces will develop in the transverse direction to reduce the building response.

5. Analysis and Results

5.1 Period of Vibration

The unclad model can be considered as a conservative assumption although the calculated story drift, the lateral displacement that occurs in a story under the wind or earthquake load, from an unclad model is larger than the actual drift from a clad model. If we compare these two models, the period of vibration (the time taken for a structure to oscillate back and forth in one complete cycle under wind or earthquake loading) of the unclad model is larger (Goodno et al., 1986). The increase in the period of vibration due to the additional cladding weights with no associated stiffness results in a decrease in the base design demand. These misdiagnoses will, therefore, influence the ground-motion demand and the building capacities.

5.1.1 Unclad Model vs. Clad Model

The period of vibration of the fundamental mode for the unclad model is 6.33 second and that in the clad models decreases as the stiffness of the cladding increases (Table 2). However, the period of vibration does not reduce as much when the stiffness of the cladding increases to a point. The period shows little difference after changing the stiffness of the cladding from $1x10^7$ to $1x10^9$ k/in. Increasing the stiffness of the cladding does not necessarily guarantee the reduction of the period. The result in Table 2 matches

Goodno and Powell's theory in 1986, except they studied the drift control contributed by the precast concrete and not the stainless steel. The added cladding panels do make an impact on the movements of the building. The additional stiffness contributed by the cladding panel will influence the coefficient of damping required. Without the cladding panels modeled in the building analysis, the stiffness is lower than its actual strength. The system does not require as much damping in the unclad model because the unclad building is softer than the clad building that it will move together with the ground when an earthquake occurs.

Table 2: Periods of unclad and clad models with lateral stayed connections in *y* direction loading

	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
T (sec)	6.3300	5.3500	5.3297	5.3108	5.3104

Table 2 shows the periods of vibration extracted from both unclad model and clad models. The unclad model that has the cladding weights added at the perimeter of the frame is still considered as a conservative assumption in the building analysis. The base shear of a building is defined by its weight multiplying the maximum spectral acceleration. Figure 23 presents the spectral acceleration verses time in the design response spectrum. Since the periods of vibration for both the clad models and the unclad model all lie in the range from 5 to 7 seconds, the spectral response acceleration, is estimated to be in the region to the right of T_L, the long-period transition period (Figure 23). The unclad model has the weight of the cladding panels added at the center of each bay; therefore, the weights of both building models are the same. The difference of the base shear demand in the unclad model and the clad model only depends on the spectral response acceleration. By the time the curve hits the period of 5 seconds, the slope of the curve is almost zero. Since the curve almost flatten out at the time of the building periods, the difference of the spectral accelerations in the clad and unclad model is not significant enough to conclude that the unclad model is a non-conservative approach.

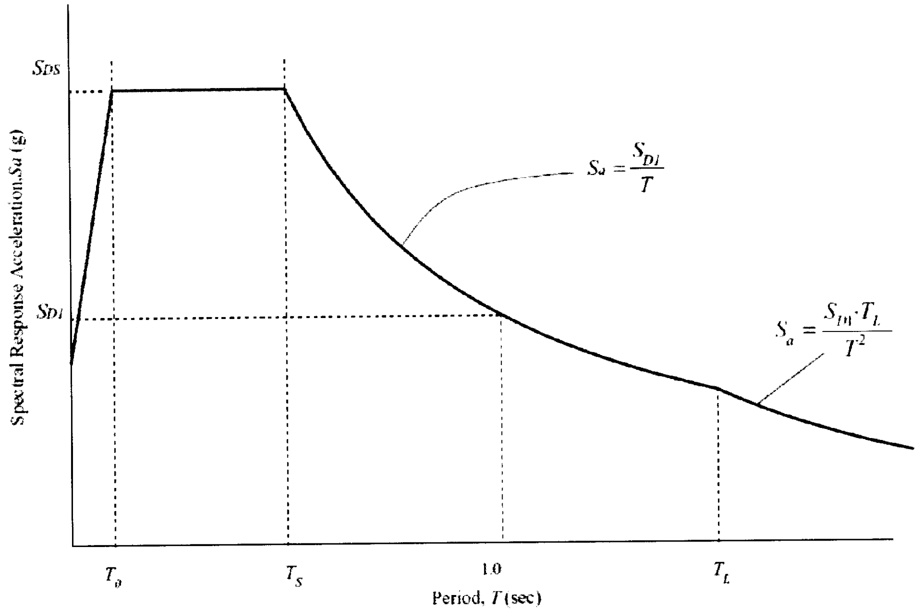


Figure 23: Design Response Spectrum (ASCE, 2005)

S_{DS} = the design spectral response acceleration parameter at short periods

S_{D1} = the design spectral response acceleration parameter at 1-s period

T = the fundamental period of the structure, s

$$T_0 = 0.2\frac{S_{D1}}{S_{DS}}$$

$$T_S = \frac{S_{D1}}{S_{DS}} \text{ and}$$

T_L = long-period transition period (s)

5.2 Seismic Loading in Y-Direction

Figure 24 displays the maximum deformation of the building after running the analysis with the Northridge Earthquake as the lateral excitation. The response of the building is scaled up to 200; actual building displacement is not as exaggerated as shown in Figure 24.

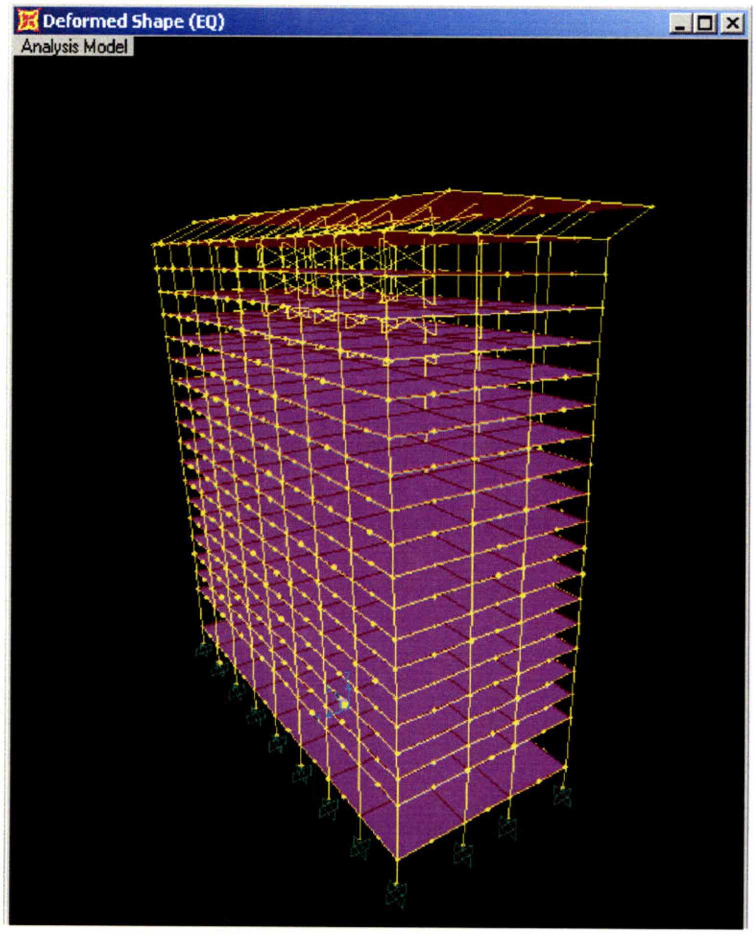


Figure 24: Maximum deformation of the building in Y direction

5.2.1 Unclad Model vs. Clad Models-Lateral Stayed Connection

Figure 25 and Figure 26 display the curves of the maximum building displacement and the interstory displacement for the unclad and the clad models over the building height. The figures indicate that steel cladding does contribute stiffness to the building. As the stiffness of the cladding increases, the response of the building under the seismic loading will decrease. However, when k, the stiffness of the cladding, reaches $1x10^9$ k/in, the building response does not have a noticeable jump from that in $k=1x10^7$ k/in. Figure 25 shows that the building does not sway as much when the cladding panels are added in the model. An increase in stiffness of the cladding will reduce the amount that the building displaces. Hence, not only does cladding contribute stiffness to a building under seismic excitation, the grade of the stainless steel cladding also influences the reaction of the building.

The cladding panels on the building façade will provide transverse shear resistance to the building motion in the plane where the loading is applied. Cladding functions like a shear wall in resisting the in-plane lateral excitation. Hence, structural engineers should treat cladding as a structural element when designing the building model.

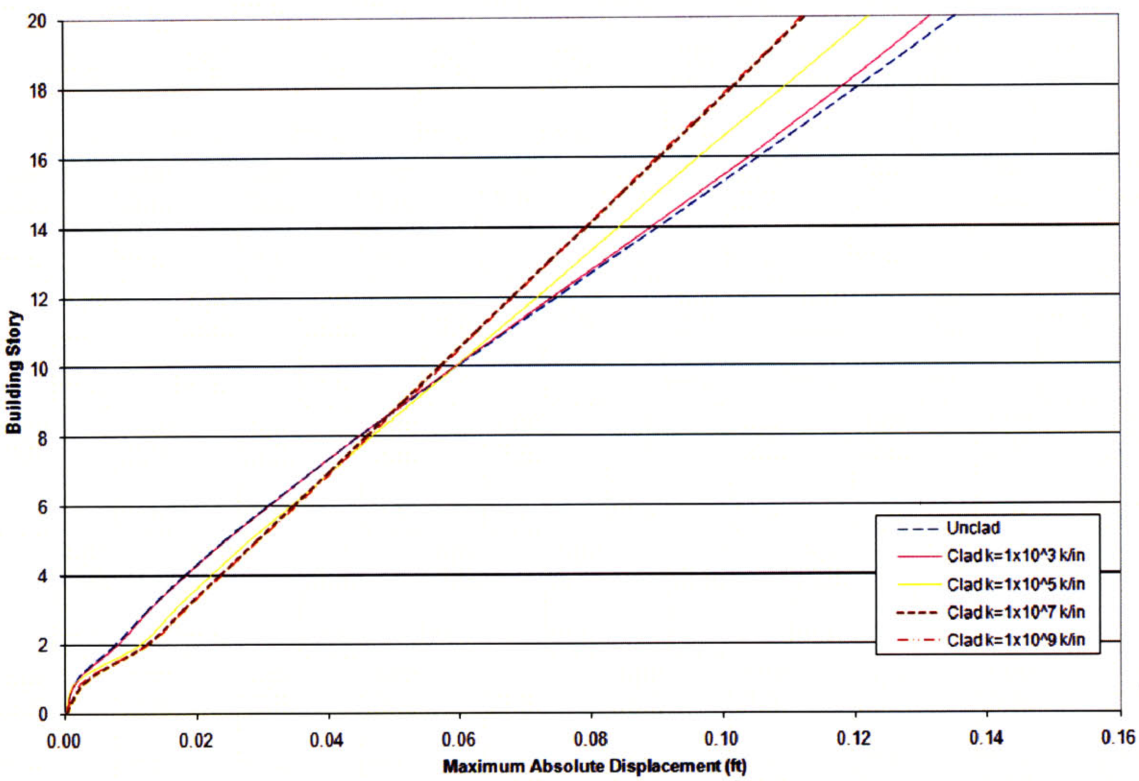


Figure 25: Comparison of maximum displacement of clad and unclad models over the building elevation in y direction loading

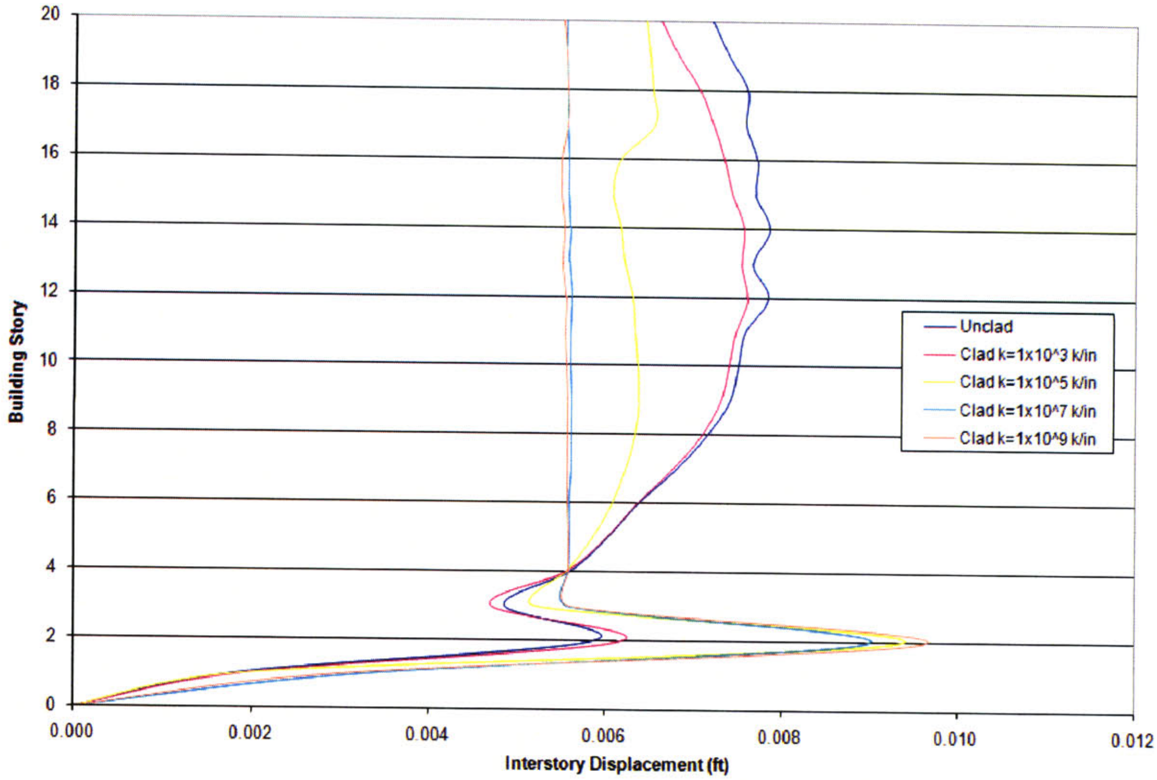


Figure 26: Comparison of interstory displacement of clad and unclad models over the story height in Y direction loading

The maximum displacement of the building for each model is given in Table 3 below. Under the earthquake excitation, the results in clad models show a decrease in the building response. The higher the cladding stiffness will result in a higher reduction in the building response. However, the building response becomes insignificant when the stiffness of the cladding reaches $1\text{x}10^9$ k/in. The clad model with the cladding stiffness of $1\text{x}10^7$ k/in can reduce the building response up to 2.28% of that in the unclad model. However, the clad model with the cladding stiffness of $1\text{x}10^9$ k/in has its building responses reduced almost the same amount as that in the clad model with $k=1\text{x}10^7$ k/in. When the cladding stiffness increases up to a point, the building response no longer decreases dramatically. The measurements of the maximum displacements and the interstory displacements are given in Appendix C.

Table 3: Comparison of the maximum displacements in clad models with that in unclad model in y direction loading

	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
$U_{maximum}$	0.135345	0.131755	0.122453	0.112584	0.112314
$U_{unclad}-U_{clad}$	N/A	0.003590	0.012892	0.022761	0.023031
$U_{unclad}-U_{clad}$ (%)	N/A	0.36%	1.29%	2.28%	2.30%

5.2.2 Lateral Stayed Connection Model vs. Rocking Connection Model

Table 4 shows the measurements of the maximum displacements in the models clad with the lateral stayed connections and the models that clad with the rocking connections. The discrepancy of the maximum displacements between the two models is small and differs at the millionth digit in feet. Hence, the dissimilarity between the rocking connection and the lateral stayed connection is very small. Even though the rocking connection is determined to be more efficient in isolating from the structural frame, it contributes less stiffness to the building compared to that in the lateral stayed connection model (Table 4). Moreover, the rocking connection is not widely employed in the United States because of its complexity in installation and high cost in erection (Bassler, 1992). Therefore, after comparing the results in Table 4, the lateral stayed connection is a better approach to be employed in connecting the cladding panels to the structural frame. The measurements of the maximum displacements and the interstory displacements in the rocking connection model are also attached in Appendix C.

Table 4: Comparison of the difference in maximum displacement between the lateral stayed connection model and rocking connection model

	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
Lateral Stayed	0.135345	0.131755	0.122453	0.112584	0.112314
Rocking	0.135345	0.131756	0.122465	0.112591	0.112319
$U_{rocking}-U_{lateral}$	0.0000%	0.0001%	0.0012%	0.0007%	0.0005%

5.3 X Direction Loading vs. Y Direction Loading

Figure 27 displays the maximum deformation of the building after running the analysis with the Northridge Earthquake applied in the *x* direction. The response of the building is scaled; actual building displacement is not as exaggerated as that shown in Figure 27.

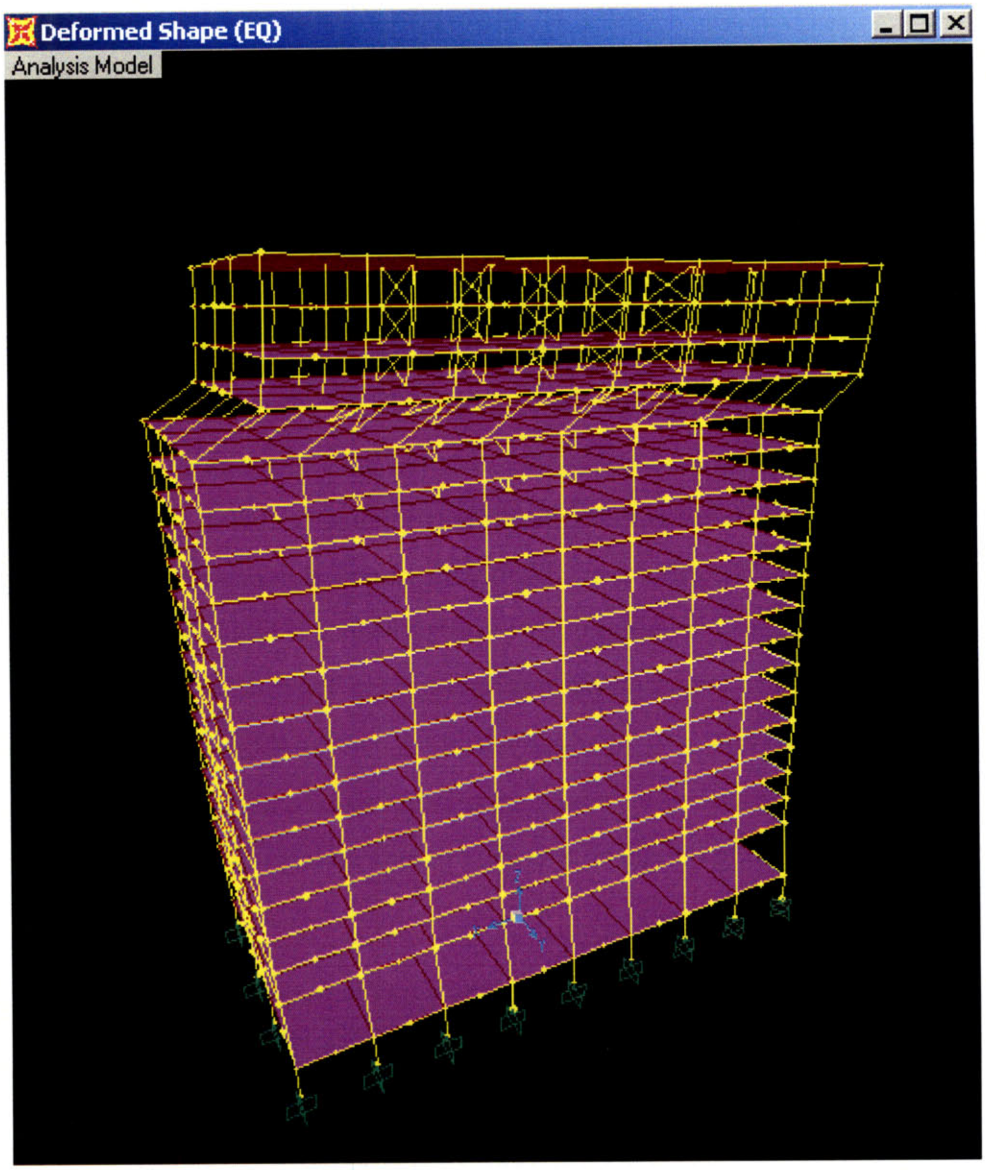


Figure 27: Maximum deformation of the building in X direction

5.3.1 Models in X Direction Loading vs. Models in Y Direction Loading

Figure 28 and Figure 29 display the curves of the maximum displacement and the interstory displacement from the clad and unclad models over the building height. The results are quite different from that in the *y* directional loading; the responses in all models are about the same in the *x* direction loading. The results of the building response in the *x* direction do not show as much difference as that in the *y* direction. The structural frame in the *x* direction is so stiff that with or without the cladding will not make a difference to the building response. There are only 4 columns in the *y* direction to resist the lateral loading. Hence, the quantity of the cladding panels added onto the structural frame of the model in the *y* direction will vary the building response significantly. Therefore, the stiffness of the cladding panel has an effect on the building response when the structural framing system is not notably stiffer than the cladding and is on the same plane as the cladding panels.

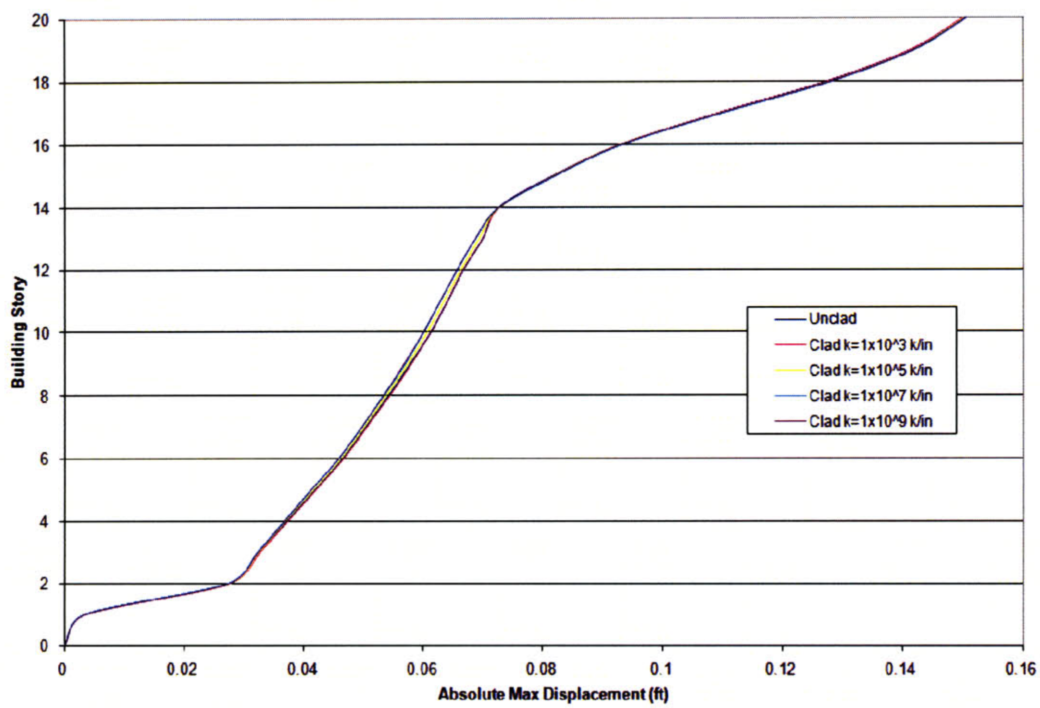


Figure 28: Comparison of maximum displacement of clad and unclad models over the building elevation in X direction loading

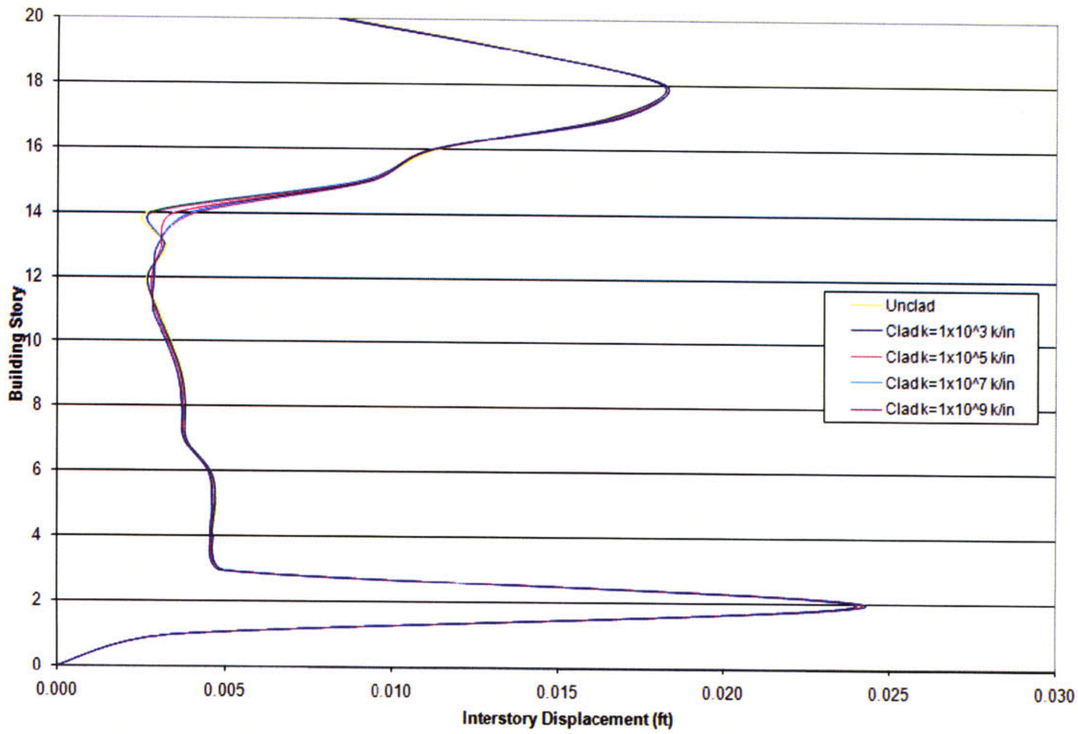


Figure 29: Comparison of interstory displacement of clad and unclad models over the building elevation in X direction loading

Shown in Figure 29 above, the interstory displacement of the *x*-direction model is significant at the second floor level compared to that in the *y*-direction. In the *x* direction loading, the moment frames at the edges are resisting the lateral motion. The x-bracings in the *y* direction are more efficient in resisting the lateral movements than the moment frames in the *x* direction. The diagonal bracings in the x-bracings contribute lateral resistance to the building together with the structural framing system. Therefore, the interstory displacements at the second floor are bigger in the *x* direction than that in the *y* direction.

Table 5: Comparison of the difference in maximum displacement between the unclad and clad models in x direction loading

	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
$U_{maximum}$	0.150301	0.150141	0.150297	0.150630	0.150642
$U_{unclad}-U_{clad}$	N/A	0.000160	0.000004	-0.000329	-0.000341
$U_{unclad}-U_{clad}$ (%)	N/A	0.02%	0.00%	-0.03%	-0.03%

Table 5 shows the measurements of the maximum displacements in the clad and unclad models. The discrepancy of the maximum displacements between that in the clad and unclad models starts at the ten-thousandth digit in feet. However, the response of the clad model actually displaces more than that in the unclad model after increasing the stiffness of the steel cladding to $1x10^7$ k/in. The cladding units in the *x* direction do not contribute as much lateral resistance to the building as that in the *y* direction. Hence, the performance of the cladding is not critical in the direction where the structural frame is too stiff.

5.3.2 Time-Displacement History

The behaviors of the time-displacement history in the *x* direction model and the *y* direction model are different. Figure 30 and 31 show distinct behavior of the building displacements over 40 seconds of the Northridge Earthquake at Joint 765. Joint 765 is the highest point of the 19-story office building that is monitored to obtain the maximum displacement in the Northridge Earthquake simulation. The maximum absolute displacement of the *x* direction model happens at 17.1 second whereas that in the *y* direction model happens at 14.4 second.

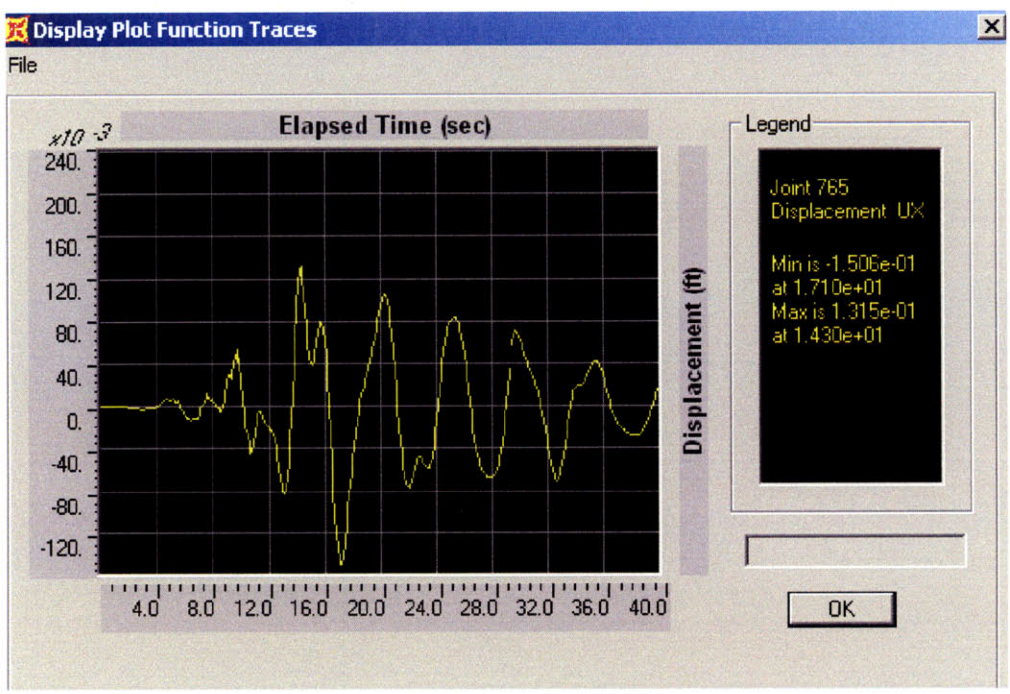


Figure 30: Time-displacement history of clad model ($k=1x10^7$ k/in) in the *x* direction loading

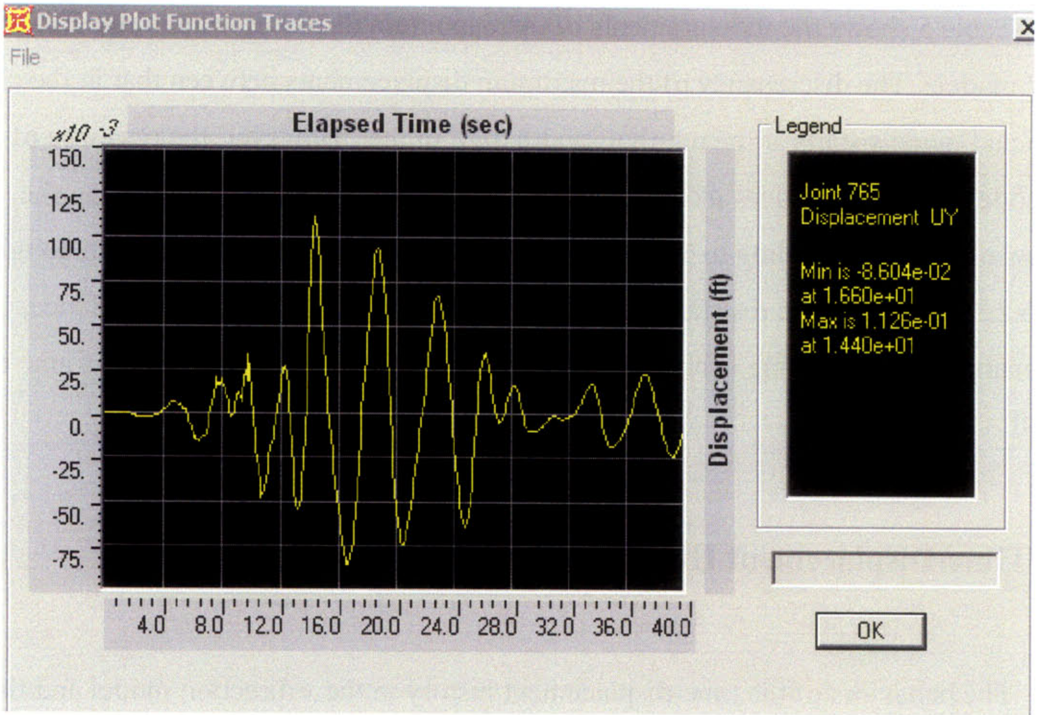


Figure 31: Time-displacement history of clad model (k=1x10^7 k/in) in the *y* direction loading

The time-displacement history plots of the unclad model and the clad models with different cladding stiffness are attached in Appendix D.

6. Conclusion

This study reports the advantages and the disadvantages of different cladding materials and cladding systems in earthquake-prone regions. Moreover, the stiffness contribution from the cladding panels to a building motion during the Northridge Earthquake is investigated in this study. The effect of cladding on mid-rise buildings in the Northridge Earthquake in the Los Angeles area is analyzed and motion resistance from the cladding to a 19-story office building in downtown Los Angeles is investigated. This 19-story office is used as a sample model in SAP2000 for the purpose of this study. Analyses of clad models and unclad models are carried out, and the results have substantiated that the clad models experience less building motion than the unclad models. The comparison of the building drift in an unclad model with that of a clad model indicates that cladding does provide significant drift control in a mid-rise building under earthquake loading. Moreover, the connection details in the cladding panels also have significant impacts on the building in the seismic response. Stainless steel cladding is selected as the exterior façade of the office building and is carefully investigated in this study. The stiffness of the stainless steel cladding has an effect on the building response when the structural framing system is not notably stiffer in that plane. Hence, interacting with the structural framing during the Northridge Earthquake, the stainless steel cladding is found to provide drift control for the building.

7. References

American Society of Civil Engineers. American Society of Civil Engineers. *American Society of Civil Engineers*. 2005.

Arnold, Chris, "Seismic Safety of the Building Envelope." Whole Building Design Guide (2008). *Building Enclosure Council*. 9 April 2009. <http://www.wbdg.org/resources/env_seismicsafety.php?r=envelope>.

Behr, Richard A., " Seismic performance of architectural glass in mid-rise curtain wall," *Journal of Architectural Engineering*, v 4, n 3, Sep, 1998, p 94-98.

Brookes, Alan, Cladding of Buildings, *E&F Spon*, London, 1998.
Bruce Bassler et al., Cladding/ Council on Tall Buildings and Urban Habitat, Committee 12A, McGraw-Hill, 1992.

Bruce L. Bassler, Marcy Li Wang and Isao Sakamoto. Cladding, *Council on Tall Buildings and Urban Habitat. Committee 12A,* McGraw-Hill, New York, 1992.

California Strong Motion Instrumentation Program. California Geological Survey (2007). *State of California. 19 April 2009. <http://www.consrv.ca.gov/CGS/smip/Pages/index.aspx>.*

Carpenter, Lauren D., "High-Rise Building Cladding Drift Accomodation," *Struct. Design Tall Spec. Build.,* Vol. 13, WHL Consulting Engineers, Los Angeles, California, USA, 2004, p. 439-456.

Charles D. Clift, Walter J. Austin, "Lateral buckling in curtain wall systems," *Journal of Structural Engineering*, v 115, n 10, Oct, 1989, p 2481-2495.

Chicago Committee on High-rise Buildings, Exterior Claddings on High-Rise Buildings: Presented at the Chicago Committee on the High Rise Buildings' 1989 Fall Symposium, *Chicago: The Committee,* 1990.

Cohen, J.M. and Powell, Graham H., "Design Study of An Energy-Dissipating Cladding System," *Earthquake Engineering & Structural Dynamics*, v 22, n 7, 1992, p 617-632.
Cohen, Julie Mark, "Seismic Performance of Cladding: Responsibility Revisited," *J. Perf. Constr. Fac.,* Vol. 9, Is. 4, ASCE, November 1995, pp. 254-270.

Goodno, B.J.and Palsson, H., "Analytical Studies of Building Cladding," *J. Struct. Engrg. Volume,* Vol. 112, Is. 4, ASCE, April 1986, pp. 665-676.

Goodno, Barry J., "Glass Curtain Wall Elements: Properties and Behavior," *ASCE J Struct Div*, v 105, n 6, Jun, 1979, p 1121-1136.

Hafsteinn Palsson, Barry J. Goodno, James I. and Craig, Kenneth M. Will, "Cladding Influence on Dynamics Response of Tall Buildings," *Earthquake Engineering & Structural Dynamics,* Vol. 12, Is.2, 1984, pp. 215-228.
Hunt, William Dudley, The contemporary curtain wall: its design, fabrication, and erection, *F.W. Dodge Corp*, New York, 1958.

International Code Council. International Building Code. *International Code Council.* 2006

Lewis, Michael D., Modern Stone Cladding: Design and Installation of Exterior Dimension Stone Systems, *ASTM Manual Series*, Philadelphia, PA, 1995.

R.A. Behr, A. Belarbi and J.H. Culp, "Dynamic racking tests of curtain wall glass elements with in-plane and out-of-plane motions," *Earthquake Engineering & Structural Dynamics*, v 24, n 1, Jan, 1995, p 1-14.

Reed, D. A, "Cladding Design for Tall Buildings," *University of Washington*, Seattle, WA, ASCE, 1986, pp. 806-807.

Richard E. Lenke, Geoffrey M.J. Williams and Howard D. Eberhart, "Cladding, " Infotech State of the Art Report, 1980, pp. 189-227.

Ting, Raymond, "Curtain wall design against story drift," *Proceedings of the 2004 Structures Congress - Building on the Past: Securing the Future, Proceedings of the 2004 Structures Congress - Building on the Past: Securing the Future*, 2004, p 661-667.

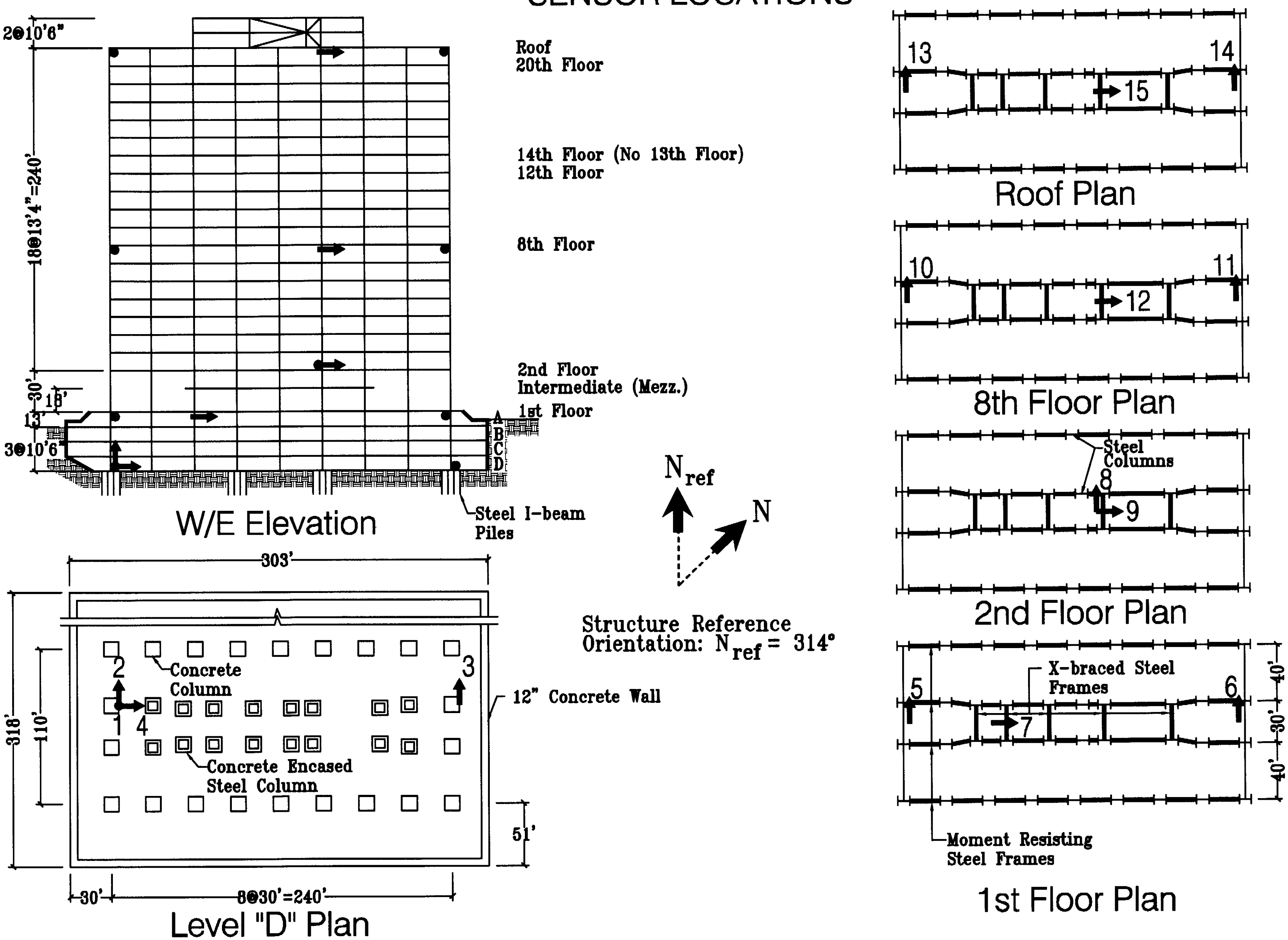
Ting, Raymond, "Functional isolation concept in curtain wall design," *AEI 2006: Building Integration Solutions - Proceedings of the 2006 Architectural Engineering National Conference*, v 2006, *AEI 2006: Building Integration Solutions - Proceedings of the 2006 Architectural Engineering National Conference*, American Society of Civil Engineers, 2006, p 13.

Weber, Richard, "Building Envelope Design Guide- Masonry Wall Systems." Whole Building Design Guide (2007). *Building Enclosure Council.* 19 April 2009. < http://www.wbdg.org/design/env_wall_masonry.php>.

Appendix A: Building Layout

Los Angeles - 19-story Office Bldg
(CSMIP Station No. 24643)

SENSOR LOCATIONS



Appendix B: The Northridge Earthquake Time History

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
0	0.0023	1.02	-0.0004	2.04	0.0047	3.06	-0.004
0.02	0.0016	1.04	0.0057	2.06	0.0112	3.08	-0.0042
0.04	0.0008	1.06	-0.0003	2.08	0.0079	3.1	0.0008
0.06	-0.0003	1.08	-0.0068	2.1	0.0041	3.12	-0.0014
0.08	-0.0016	1.1	-0.0021	2.12	0.0075	3.14	-0.0095
0.1	-0.0002	1.12	0.0032	2.14	0.0136	3.16	-0.0047
0.12	0.0015	1.14	-0.0039	2.16	0.0145	3.18	0.0035
0.14	0.0014	1.16	-0.0057	2.18	0.0133	3.2	-0.0039
0.16	0.0014	1.18	-0.0037	2.2	0.0124	3.22	-0.0099
0.18	0.0002	1.2	-0.0037	2.22	0.0079	3.24	-0.0047
0.2	-0.0018	1.22	0.0015	2.24	0.0018	3.26	0.0057
0.22	-0.0006	1.24	0.0017	2.26	-0.0048	3.28	0.008
0.24	0.0003	1.26	0.0003	2.28	-0.0109	3.3	0.0007
0.26	-0.0001	1.28	-0.0022	2.3	-0.0162	3.32	-0.0008
0.28	0.001	1.3	-0.0049	2.32	-0.0169	3.34	0.0068
0.3	0.0019	1.32	0.0004	2.34	-0.0101	3.36	0.0056
0.32	0.0012	1.34	0.0019	2.36	-0.0046	3.38	0.0044
0.34	-0.0013	1.36	0.0062	2.38	0.0034	3.4	-0.0041
0.36	-0.0005	1.38	0.0063	2.4	0.0103	3.42	-0.0195
0.38	0.001	1.4	-0.0004	2.42	0.0058	3.44	-0.0141
0.4	0.0017	1.42	-0.0001	2.44	0.002	3.46	-0.0011
0.42	0.0013	1.44	0.0082	2.46	0.0057	3.48	0.0017
0.44	-0.0014	1.46	0.0154	2.48	0.0071	3.5	0.0021
0.46	-0.0017	1.48	0.0097	2.5	0.0033	3.52	-0.0027
0.48	-0.0006	1.5	0.0026	2.52	-0.0067	3.54	-0.0078
0.5	0.0033	1.52	-0.0037	2.54	-0.0144	3.56	0.0039
0.52	0.0047	1.54	-0.0012	2.56	-0.0093	3.58	0.0176
0.54	-0.0001	1.56	0.003	2.58	0.0009	3.6	0.0148
0.56	-0.0022	1.58	-0.0053	2.6	0.0007	3.62	0.0015
0.58	0	1.6	-0.0127	2.62	-0.0078	3.64	-0.0037
0.6	0.0024	1.62	-0.01	2.64	-0.01	3.66	0.0005
0.62	0.004	1.64	-0.0051	2.66	-0.0122	3.68	0.0045
0.64	0.0032	1.66	-0.0059	2.68	-0.0085	3.7	0.006
0.66	-0.002	1.68	-0.0092	2.7	-0.0045	3.72	-0.0016
0.68	-0.0049	1.7	-0.0088	2.72	-0.0077	3.74	-0.0011
0.7	-0.0004	1.72	-0.0075	2.74	-0.0082	3.76	0.0033
0.72	0.005	1.74	-0.0059	2.76	-0.0059	3.78	-0.0039
0.74	0.0028	1.76	0.0006	2.78	0.004	3.8	-0.0031
0.76	-0.0008	1.78	0.0071	2.8	0.0176	3.82	0.0104
0.78	-0.002	1.8	0.006	2.82	0.018	3.84	0.0158
0.8	-0.004	1.82	0.0011	2.84	0.0055	3.86	0.0064
0.82	-0.0016	1.84	0.0053	2.86	0.0029	3.88	-0.0052
0.84	0.0004	1.86	0.008	2.88	0.0058	3.9	-0.0054
0.86	-0.0008	1.88	0.0008	2.9	0.0062	3.92	0.0098
0.88	-0.0035	1.9	-0.0083	2.92	0.0039	3.94	0.0177
0.9	-0.0015	1.92	-0.0115	2.94	0.0027	3.96	0.0014
0.92	0.0054	1.94	-0.0067	2.96	0.0069	3.98	-0.0192
0.94	0.0005	1.96	-0.0045	2.98	0.0086	4	-0.0208
0.96	-0.0033	1.98	-0.006	3	0.0056	4.02	0.0007
0.98	-0.0021	2	-0.0088	3.02	0.0029	4.04	0.0272
1	-0.0065	2.02	-0.0065	3.04	0.0025	4.06	0.0261

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
4.08	0.0012	5.1	-0.0513	6.12	0.0845	7.14	-0.0889
4.1	-0.0151	5.12	0.0994	6.14	0.0485	7.16	-0.102
4.12	-0.0056	5.14	0.124	6.16	-0.0264	7.18	-0.0677
4.14	0.0165	5.16	0.0061	6.18	-0.0439	7.2	0.0195
4.16	0.0223	5.18	-0.0811	6.2	-0.104	7.22	0.0378
4.18	-0.0004	5.2	-0.0582	6.22	-0.212	7.24	0.0372
4.2	-0.0139	5.22	0.0142	6.24	-0.154	7.26	0.031
4.22	-0.0014	5.24	0.075	6.26	-0.0082	7.28	-0.0045
4.24	0.0053	5.26	0.0561	6.28	0.0253	7.3	-0.0283
4.26	-0.0032	5.28	-0.0067	6.3	0.0286	7.32	-0.0335
4.28	-0.0095	5.3	-0.0173	6.32	0.03	7.34	-0.0297
4.3	-0.0077	5.32	-0.0608	6.34	0.0424	7.36	-0.033
4.32	-0.0034	5.34	-0.0616	6.36	0.0522	7.38	0.0503
4.34	-0.0001	5.36	0.0868	6.38	0.0574	7.4	0.156
4.36	0.0049	5.38	0.154	6.4	0.0621	7.42	0.181
4.38	-0.0004	5.4	0.0792	6.42	0.0673	7.44	0.122
4.4	0.0015	5.42	-0.0421	6.44	0.0442	7.46	0.0541
4.42	0.0096	5.44	-0.102	6.46	-0.0174	7.48	0.0604
4.44	0.0314	5.46	-0.111	6.48	-0.0425	7.5	-0.0144
4.46	0.059	5.48	-0.0596	6.5	-0.0544	7.52	-0.169
4.48	0.0781	5.5	-0.0304	6.52	-0.0699	7.54	-0.193
4.5	0.0338	5.52	-0.0826	6.54	-0.0397	7.56	-0.146
4.52	-0.0617	5.54	-0.111	6.56	0.021	7.58	-0.11
4.54	-0.0934	5.56	-0.0345	6.58	0.0055	7.6	-0.135
4.56	-0.0835	5.58	0.0753	6.6	-0.0304	7.62	-0.197
4.58	-0.0734	5.6	0.0901	6.62	-0.0463	7.64	-0.209
4.6	-0.0487	5.62	0.0761	6.64	-0.0083	7.66	-0.166
4.62	-0.0227	5.64	0.0573	6.66	0.0614	7.68	0.0375
4.64	0.0297	5.66	-0.0765	6.68	0.0787	7.7	0.194
4.66	0.124	5.68	-0.142	6.7	0.0157	7.72	0.211
4.68	0.158	5.7	0.0025	6.72	-0.0506	7.74	0.229
4.7	0.0765	5.72	0.118	6.74	-0.0383	7.76	0.205
4.72	-0.0127	5.74	0.0829	6.76	-0.0408	7.78	0.0373
4.74	-0.0904	5.76	-0.0099	6.78	-0.0699	7.8	-0.0655
4.76	-0.156	5.78	-0.0296	6.8	-0.0336	7.82	-0.0293
4.78	-0.171	5.8	0.0172	6.82	0.0428	7.84	0.0043
4.8	-0.0756	5.82	0.0706	6.84	0.0854	7.86	-0.0259
4.82	0.106	5.84	-0.0245	6.86	0.117	7.88	-0.131
4.84	0.148	5.86	-0.122	6.88	0.0993	7.9	-0.132
4.86	0.0333	5.88	-0.104	6.9	0.0503	7.92	-0.0285
4.88	-0.0771	5.9	-0.0949	6.92	0.0474	7.94	0.0407
4.9	-0.0813	5.92	-0.1	6.94	0.0465	7.96	0.0433
4.92	-0.0324	5.94	-0.0662	6.96	0.0259	7.98	0.0281
4.94	0.0258	5.96	0.0768	6.98	0.0145	8	0.0163
4.96	0.112	5.98	0.089	7	0.0409	8.02	0.0238
4.98	0.167	6	-0.0192	7.02	0.0214	8.04	0.0468
5	0.113	6.02	-0.0056	7.04	-0.0443	8.06	0.0228
5.02	0.0178	6.04	0.0974	7.06	-0.0127	8.08	-0.0266
5.04	-0.0944	6.06	0.149	7.08	0.02	8.1	-0.0334
5.06	-0.163	6.08	0.129	7.1	0.024	8.12	-0.0423
5.08	-0.156	6.1	0.0924	7.12	-0.0231	8.14	-0.0543

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
8.16	-0.0648	9.18	-0.169	10.2	0.0435	11.22	-0.0487
8.18	-0.0733	9.2	-0.0708	10.22	-0.234	11.24	-0.0762
8.2	-0.0399	9.22	0.0477	10.24	-0.324	11.26	-0.0284
8.22	-0.0252	9.24	0.131	10.26	-0.237	11.28	0.0382
8.24	-0.0334	9.26	0.155	10.28	0.043	11.3	0.008
8.26	-0.0546	9.28	0.158	10.3	0.326	11.32	-0.0645
8.28	-0.0058	9.3	0.134	10.32	0.314	11.34	-0.105
8.3	0.113	9.32	0.0719	10.34	0.111	11.36	-0.0698
8.32	0.168	9.34	0.0609	10.36	0.0717	11.38	-0.0394
8.34	0.122	9.36	0.0884	10.38	0.116	11.4	-0.0343
8.36	0.0147	9.38	0.129	10.4	0.0882	11.42	-0.0349
8.38	-0.0983	9.4	0.169	10.42	-0.0229	11.44	-0.0076
8.4	-0.142	9.42	0.194	10.44	-0.152	11.46	0.0428
8.42	-0.0712	9.44	0.205	10.46	-0.233	11.48	0.0663
8.44	-0.046	9.46	0.193	10.48	-0.264	11.5	0.0754
8.46	-0.0483	9.48	0.138	10.5	-0.229	11.52	0.0741
8.48	-0.027	9.5	0.0274	10.52	-0.0697	11.54	0.0489
8.5	0.016	9.52	-0.161	10.54	0.0071	11.56	0.0163
8.52	0.0622	9.54	-0.234	10.56	-0.0549	11.58	0.0137
8.54	0.121	9.56	-0.29	10.58	-0.145	11.6	0.0089
8.56	0.141	9.58	-0.399	10.6	-0.113	11.62	-0.0129
8.58	0.12	9.6	-0.506	10.62	0.0369	11.64	-0.027
8.6	0.0969	9.62	-0.442	10.64	0.191	11.66	0.0038
8.62	0.0913	9.64	0.0527	10.66	0.336	11.68	0.0312
8.64	0.068	9.66	0.61	10.68	0.356	11.7	0.0129
8.66	-0.0378	9.68	0.753	10.7	0.237	11.72	-0.0002
8.68	-0.0755	9.7	0.588	10.72	0.0221	11.74	0.0103
8.7	-0.095	9.72	0.326	10.74	-0.124	11.76	0.0348
8.72	-0.0675	9.74	0.195	10.76	-0.075	11.78	0.0524
8.74	0.126	9.76	-0.0731	10.78	0.0857	11.8	0.073
8.76	0.213	9.78	-0.657	10.8	0.136	11.82	0.0638
8.78	0.12	9.8	-0.883	10.82	0.0571	11.84	-0.0399
8.8	-0.0524	9.82	-0.71	10.84	0.0187	11.86	-0.0943
8.82	-0.125	9.84	-0.362	10.86	0.0328	11.88	-0.0678
8.84	-0.0288	9.86	-0.13	10.88	0.0929	11.9	-0.0427
8.86	0.101	9.88	-0.118	10.9	0.115	11.92	-0.0337
8.88	0.214	9.9	-0.0197	10.92	0.0683	11.94	-0.0007
8.9	0.221	9.92	0.223	10.94	0.0248	11.96	0.0385
8.92	0.127	9.94	0.251	10.96	0.0006	11.98	0.0489
8.94	0.009	9.96	0.0485	10.98	-0.0547	12	0.0282
8.96	-0.101	9.98	-0.111	11	-0.101	12.02	-0.0023
8.98	-0.145	10	-0.144	11.02	-0.0889	12.04	-0.002
9	-0.133	10.02	-0.14	11.04	-0.0022	12.06	0.0251
9.02	-0.0525	10.04	-0.152	11.06	0.06	12.08	0.0393
9.04	0.0196	10.06	-0.087	11.08	0.0243	12.1	0.0397
9.06	0.0171	10.08	0.0336	11.1	-0.0292	12.12	0.0059
9.08	-0.0273	10.1	0.13	11.12	-0.0448	12.14	-0.0747
9.1	-0.113	10.12	0.166	11.14	-0.0406	12.16	-0.104
9.12	-0.169	10.14	0.177	11.16	-0.0353	12.18	-0.0466
9.14	-0.181	10.16	0.231	11.18	-0.0275	12.2	0.0202
9.16	-0.183	10.18	0.282	11.2	-0.0339	12.22	-0.0432

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
12.24	-0.118	13.26	0.0335	14.28	-0.169	15.3	0.0348
12.26	-0.129	13.28	0.0542	14.3	-0.164	15.32	0.0442
12.28	-0.128	13.3	0.0756	14.32	-0.161	15.34	0.0373
12.3	-0.0757	13.32	0.0866	14.34	-0.149	15.36	0.0225
12.32	-0.022	13.34	0.0834	14.36	-0.121	15.38	0.0083
12.34	-0.019	13.36	0.0689	14.38	-0.0933	15.4	0.0013
12.36	-0.0373	13.38	0.0538	14.4	-0.0805	15.42	-0.0038
12.38	-0.0577	13.4	0.0469	14.42	-0.0751	15.44	-0.0085
12.4	-0.0643	13.42	0.0481	14.44	-0.0685	15.46	-0.0065
12.42	-0.0629	13.44	0.0516	14.46	-0.0548	15.48	-0.0067
12.44	-0.0568	13.46	0.0459	14.48	-0.0241	15.5	-0.0134
12.46	-0.0598	13.48	0.0351	14.5	0.0063	15.52	-0.0236
12.48	-0.0775	13.5	0.0272	14.52	0.0113	15.54	-0.0248
12.5	-0.0919	13.52	0.0329	14.54	0.0054	15.56	-0.0128
12.52	-0.0945	13.54	0.0459	14.56	-0.0043	15.58	0.0024
12.54	-0.0869	13.56	0.0492	14.58	-0.0093	15.6	0.0131
12.56	-0.0826	13.58	0.0461	14.6	-0.0003	15.62	0.0111
12.58	-0.0852	13.6	0.0595	14.62	0.0147	15.64	-0.0018
12.6	-0.0863	13.62	0.074	14.64	0.0324	15.66	-0.0184
12.62	-0.0803	13.64	0.0698	14.66	0.0389	15.68	-0.03
12.64	-0.0639	13.66	0.0575	14.68	0.0309	15.7	-0.0303
12.66	0.005	13.68	0.0469	14.7	-0.023	15.72	-0.0203
12.68	0.0568	13.7	0.0506	14.72	-0.065	15.74	-0.0072
12.7	0.0548	13.72	0.0707	14.74	-0.0649	15.76	0.0022
12.72	0.0267	13.74	0.0987	14.76	-0.0363	15.78	-0.0042
12.74	-0.016	13.76	0.117	14.78	0.0059	15.8	-0.0164
12.76	-0.0484	13.78	0.118	14.8	0.0194	15.82	-0.0257
12.78	-0.0655	13.8	0.111	14.82	0.0205	15.84	-0.0235
12.8	-0.0598	13.82	0.113	14.84	0.0156	15.86	-0.0094
12.82	-0.0141	13.84	0.115	14.86	0.0203	15.88	0.0088
12.84	0.0226	13.86	0.11	14.88	0.0273	15.9	0.024
12.86	0.0219	13.88	0.103	14.9	0.039	15.92	0.0222
12.88	0.0147	13.9	0.102	14.92	0.051	15.94	0.0059
12.9	0.0097	13.92	0.106	14.94	0.0623	15.96	-0.0121
12.92	0.0165	13.94	0.101	14.96	0.0701	15.98	-0.0245
12.94	0.0305	13.96	0.0856	14.98	0.0708	16	-0.0255
12.96	0.0492	13.98	0.0456	15	0.0607	16.02	-0.0194
12.98	0.0567	14	-0.0129	15.02	0.0381	16.04	-0.0204
13	0.0461	14.02	-0.0923	15.04	0.0177	16.06	-0.0293
13.02	0.0313	14.04	-0.127	15.06	0.0071	16.08	-0.0341
13.04	0.034	14.06	-0.122	15.08	0.009	16.1	-0.0333
13.06	0.0473	14.08	-0.0961	15.1	0.0238	16.12	-0.03
13.08	0.0652	14.1	-0.0717	15.12	0.0474	16.14	-0.0211
13.1	0.0783	14.12	-0.0637	15.14	0.0681	16.16	-0.0088
13.12	0.0831	14.14	-0.0595	15.16	0.0737	16.18	-0.0027
13.14	0.0815	14.16	-0.0725	15.18	0.0542	16.2	-0.0136
13.16	0.0843	14.18	-0.095	15.2	0.0157	16.22	-0.0297
13.18	0.0877	14.2	-0.125	15.22	-0.008	16.24	-0.0385
13.2	0.0925	14.22	-0.15	15.24	-0.013	16.26	-0.0378
13.22	0.0696	14.24	-0.166	15.26	-0.0051	16.28	-0.0392
13.24	0.0295	14.26	-0.172	15.28	0.0147	16.3	-0.046

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
16.32	-0.057	17.34	0.0467	18.36	0.0198	19.38	-0.0183
16.34	-0.0613	17.36	0.0465	18.38	0.0135	19.4	-0.0281
16.36	-0.0446	17.38	0.0305	18.4	0.0046	19.42	-0.0295
16.38	-0.021	17.4	0.0076	18.42	-0.0044	19.44	-0.023
16.4	-0.0078	17.42	-0.0063	18.44	-0.0096	19.46	-0.012
16.42	-0.0112	17.44	-0.0043	18.46	-0.0113	19.48	0.0002
16.44	-0.0144	17.46	-0.0055	18.48	-0.0097	19.5	0.0121
16.46	-0.0077	17.48	-0.0127	18.5	-0.0091	19.52	0.0222
16.48	0.0058	17.5	-0.0236	18.52	-0.0146	19.54	0.0251
16.5	0.017	17.52	-0.0354	18.54	-0.0211	19.56	0.0143
16.52	0.0176	17.54	-0.0458	18.56	-0.0272	19.58	-0.0026
16.54	0.0147	17.56	-0.0549	18.58	-0.0301	19.6	-0.0175
16.56	0.0177	17.58	-0.0629	18.6	-0.0331	19.62	-0.0174
16.58	0.0265	17.6	-0.0702	18.62	-0.0293	19.64	-0.0059
16.6	0.0353	17.62	-0.0745	18.64	-0.0167	19.66	0.0097
16.62	0.0397	17.64	-0.0689	18.66	-0.0026	19.68	0.0257
16.64	0.041	17.66	-0.0531	18.68	0.0042	19.7	0.0356
16.66	0.0431	17.68	-0.0364	18.7	-0.0009	19.72	0.0349
16.68	0.038	17.7	-0.022	18.72	-0.0091	19.74	0.0241
16.7	0.0279	17.72	-0.012	18.74	-0.0106	19.76	0.0146
16.72	0.0185	17.74	-0.0021	18.76	-0.0052	19.78	0.0123
16.74	0.0121	17.76	0.0043	18.78	-0.0006	19.8	0.0153
16.76	0.0084	17.78	0.0041	18.8	0.0002	19.82	0.0199
16.78	0.0043	17.8	0.0069	18.82	-0.0047	19.84	0.0247
16.8	-0.0036	17.82	0.0141	18.84	-0.0124	19.86	0.0235
16.82	-0.0173	17.84	0.0189	18.86	-0.0203	19.88	0.02
16.84	-0.032	17.86	0.0209	18.88	-0.0248	19.9	0.0223
16.86	-0.0465	17.88	0.0191	18.9	-0.0247	19.92	0.022
16.88	-0.0495	17.9	0.012	18.92	-0.0246	19.94	0.0162
16.9	-0.039	17.92	0.0005	18.94	-0.0191	19.96	0.0114
16.92	-0.0275	17.94	-0.0019	18.96	-0.0088	19.98	0.0169
16.94	-0.0191	17.96	0.0156	18.98	0.0023	20	0.0301
16.96	-0.017	17.98	0.0383	19	0.0133	20.02	0.039
16.98	-0.0155	18	0.0513	19.02	0.0151	20.04	0.0348
17	-0.0091	18.02	0.0511	19.04	0.006	20.06	0.024
17.02	0.0008	18.04	0.0466	19.06	-0.0014	20.08	0.018
17.04	0.0091	18.06	0.0401	19.08	-0.0046	20.1	0.0132
17.06	0.0138	18.08	0.0342	19.1	-0.0129	20.12	0.0144
17.08	0.0178	18.1	0.0269	19.12	-0.0246	20.14	0.0222
17.1	0.0237	18.12	0.0159	19.14	-0.03	20.16	0.0289
17.12	0.028	18.14	0.015	19.16	-0.0247	20.18	0.0258
17.14	0.0314	18.16	0.0255	19.18	-0.0234	20.2	0.0165
17.16	0.0395	18.18	0.0401	19.2	-0.0293	20.22	0.0092
17.18	0.048	18.2	0.0476	19.22	-0.0316	20.24	0.0037
17.2	0.0546	18.22	0.0412	19.24	-0.0328	20.26	-0.0015
17.22	0.0535	18.24	0.029	19.26	-0.0418	20.28	-0.008
17.24	0.0446	18.26	0.0172	19.28	-0.0425	20.3	-0.0121
17.26	0.035	18.28	0.0095	19.3	-0.0292	20.32	-0.0137
17.28	0.0285	18.3	0.0065	19.32	-0.0132	20.34	-0.0118
17.3	0.0325	18.32	0.0064	19.34	-0.0064	20.36	-0.0056
17.32	0.0396	18.34	0.0141	19.36	-0.0101	20.38	0.0001

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
20.4	0.0046	21.42	-0.0243	22.44	0.0066	23.46	-0.0107
20.42	0.0082	21.44	-0.0161	22.46	0.0104	23.48	-0.0092
20.44	0.0115	21.46	-0.0117	22.48	0.0088	23.5	-0.0054
20.46	0.0138	21.48	-0.0116	22.5	0.0029	23.52	-0.0031
20.48	0.0115	21.5	-0.0114	22.52	-0.0081	23.54	-0.0022
20.5	0.0086	21.52	-0.0153	22.54	-0.0175	23.56	0.0017
20.52	0.0081	21.54	-0.0214	22.56	-0.0214	23.58	0.0052
20.54	0.0122	21.56	-0.022	22.58	-0.0238	23.6	0.004
20.56	0.0168	21.58	-0.0196	22.6	-0.0249	23.62	-0.0031
20.58	0.0119	21.6	-0.0161	22.62	-0.0226	23.64	-0.0053
20.6	0.0035	21.62	-0.0164	22.64	-0.0182	23.66	0.0007
20.62	-0.0058	21.64	-0.0155	22.66	-0.0156	23.68	0.0038
20.64	-0.0103	21.66	-0.0123	22.68	-0.0142	23.7	0.0051
20.66	-0.0083	21.68	-0.007	22.7	-0.0131	23.72	0.0053
20.68	-0.0032	21.7	0.0018	22.72	-0.0091	23.74	0.0022
20.7	0.0011	21.72	0.0076	22.74	-0.0044	23.76	-0.0017
20.72	0.0008	21.74	0.0062	22.76	0.0007	23.78	-0.0041
20.74	-0.0032	21.76	0.0018	22.78	0.0044	23.8	-0.0027
20.76	-0.0097	21.78	0.0018	22.8	0.0013	23.82	0.0024
20.78	-0.0095	21.8	0.0039	22.82	-0.0033	23.84	0.0031
20.8	-0.0064	21.82	0.0063	22.84	-0.0046	23.86	-0.0031
20.82	-0.0067	21.84	0.0054	22.86	-0.0054	23.88	-0.0089
20.84	-0.0122	21.86	0.0093	22.88	-0.0099	23.9	-0.0096
20.86	-0.0182	21.88	0.0172	22.9	-0.0158	23.92	-0.0047
20.88	-0.0228	21.9	0.0218	22.92	-0.0151	23.94	0.0001
20.9	-0.0286	21.92	0.0208	22.94	-0.0092	23.96	0.0036
20.92	-0.0294	21.94	0.0202	22.96	-0.0086	23.98	0.0036
20.94	-0.0226	21.96	0.0263	22.98	-0.0117	24	0.0038
20.96	-0.0146	21.98	0.0321	23	-0.0088	24.02	0.0024
20.98	-0.0123	22	0.0334	23.02	0.0021	24.04	-0.0008
21	-0.0157	22.02	0.0284	23.04	0.0115	24.06	-0.0044
21.02	-0.0174	22.04	0.0215	23.06	0.0126	24.08	-0.0054
21.04	-0.0194	22.06	0.0168	23.08	0.0097	24.1	-0.0011
21.06	-0.0218	22.08	0.0187	23.1	0.0066	24.12	0.0017
21.08	-0.0225	22.1	0.0269	23.12	0.0057	24.14	0.0018
21.1	-0.0226	22.12	0.0371	23.14	0.0078	24.16	0.0012
21.12	-0.0186	22.14	0.0442	23.16	0.0091	24.18	0.0008
21.14	-0.0112	22.16	0.047	23.18	0.0041	24.2	-0.0019
21.16	-0.003	22.18	0.0454	23.2	-0.0033	24.22	-0.0033
21.18	-0.0004	22.2	0.0401	23.22	-0.01	24.24	-0.0043
21.2	-0.0017	22.22	0.0332	23.24	-0.0148	24.26	-0.006
21.22	-0.0004	22.24	0.0242	23.26	-0.0177	24.28	-0.0058
21.24	0.0014	22.26	0.0125	23.28	-0.019	24.3	-0.0039
21.26	-0.0031	22.28	0.001	23.3	-0.016	24.32	-0.0004
21.28	-0.0058	22.3	-0.0068	23.32	-0.0129	24.34	0.002
21.3	0.0003	22.32	-0.0058	23.34	-0.013	24.36	0.0056
21.32	0.0048	22.34	0.0008	23.36	-0.0153	24.38	0.0062
21.34	0.0041	22.36	0.0054	23.38	-0.0128	24.4	0.0034
21.36	-0.0052	22.38	0.0051	23.4	-0.0094	24.42	0.0013
21.38	-0.0185	22.4	0.0031	23.42	-0.0102	24.44	0.0037
21.4	-0.027	22.42	0.0031	23.44	-0.0112	24.46	0.0057

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
24.48	0.0034	25.5	-0.0141	26.52	-0.0018	27.54	0.0069
24.5	0.0025	25.52	-0.0129	26.54	0.0044	27.56	0.0079
24.52	0.0015	25.54	-0.0115	26.56	0.011	27.58	0.0078
24.54	-0.0022	25.56	-0.0107	26.58	0.0137	27.6	0.0095
24.56	-0.0042	25.58	-0.0124	26.6	0.0148	27.62	0.0087
24.58	-0.0018	25.6	-0.0156	26.62	0.012	27.64	0.0065
24.6	0.0003	25.62	-0.0198	26.64	0.012	27.66	0.0027
24.62	0.0035	25.64	-0.023	26.66	0.0146	27.68	-0.0026
24.64	0.0087	25.66	-0.0249	26.68	0.0165	27.7	-0.0056
24.66	0.0155	25.68	-0.0231	26.7	0.0188	27.72	-0.0085
24.68	0.0174	25.7	-0.0225	26.72	0.0193	27.74	-0.0091
24.7	0.0131	25.72	-0.0244	26.74	0.0194	27.76	-0.009
24.72	0.0112	25.74	-0.0281	26.76	0.021	27.78	-0.0066
24.74	0.0128	25.76	-0.0312	26.78	0.0244	27.8	-0.0021
24.76	0.0173	25.78	-0.0313	26.8	0.0281	27.82	0.0007
24.78	0.0213	25.8	-0.0296	26.82	0.0304	27.84	0.0007
24.8	0.0248	25.82	-0.0294	26.84	0.0312	27.86	-0.0007
24.82	0.0296	25.84	-0.0297	26.86	0.0282	27.88	-0.0056
24.84	0.0314	25.86	-0.0294	26.88	0.0264	27.9	-0.0111
24.86	0.0325	25.88	-0.0291	26.9	0.0272	27.92	-0.0159
24.88	0.0284	25.9	-0.0275	26.92	0.0299	27.94	-0.019
24.9	0.0251	25.92	-0.0291	26.94	0.0318	27.96	-0.0189
24.92	0.0225	25.94	-0.0321	26.96	0.0314	27.98	-0.0159
24.94	0.0209	25.96	-0.034	26.98	0.0303	28	-0.0119
24.96	0.0223	25.98	-0.0359	27	0.0255	28.02	-0.0101
24.98	0.0248	26	-0.0361	27.02	0.0212	28.04	-0.0096
25	0.0277	26.02	-0.0347	27.04	0.0226	28.06	-0.0102
25.02	0.0261	26.04	-0.0325	27.06	0.0272	28.08	-0.0111
25.04	0.0249	26.06	-0.0306	27.08	0.0308	28.1	-0.01
25.06	0.0208	26.08	-0.0316	27.1	0.0315	28.12	-0.0081
25.08	0.0179	26.1	-0.0301	27.12	0.0297	28.14	-0.0078
25.1	0.018	26.12	-0.027	27.14	0.0255	28.16	-0.0112
25.12	0.0198	26.14	-0.024	27.16	0.0224	28.18	-0.0166
25.14	0.0216	26.16	-0.0201	27.18	0.02	28.2	-0.0187
25.16	0.0221	26.18	-0.0168	27.2	0.0174	28.22	-0.0186
25.18	0.021	26.2	-0.0168	27.22	0.0154	28.24	-0.0158
25.2	0.0168	26.22	-0.021	27.24	0.0143	28.26	-0.0137
25.22	0.0125	26.24	-0.0278	27.26	0.0147	28.28	-0.0099
25.24	0.0108	26.26	-0.0324	27.28	0.0153	28.3	-0.0098
25.26	0.009	26.28	-0.0341	27.3	0.0161	28.32	-0.0126
25.28	0.0063	26.3	-0.031	27.32	0.0133	28.34	-0.0143
25.3	0.006	26.32	-0.0252	27.34	0.0083	28.36	-0.0147
25.32	0.0053	26.34	-0.0218	27.36	0.0081	28.38	-0.015
25.34	0.0013	26.36	-0.0202	27.38	0.0098	28.4	-0.0165
25.36	-0.0027	26.38	-0.0184	27.4	0.01	28.42	-0.0145
25.38	-0.0024	26.4	-0.0147	27.42	0.0105	28.44	-0.0123
25.4	-0.0022	26.42	-0.0124	27.44	0.0123	28.46	-0.0116
25.42	-0.0032	26.44	-0.0129	27.46	0.0157	28.48	-0.014
25.44	-0.0061	26.46	-0.0131	27.48	0.0181	28.5	-0.0142
25.46	-0.0101	26.48	-0.0111	27.5	0.0169	28.52	-0.0118
25.48	-0.0134	26.5	-0.0061	27.52	0.0108	28.54	-0.0062

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
28.56	-0.0023	29.58	-0.0063	30.6	-0.0021	31.62	0.0067
28.58	-0.0002	29.6	-0.0029	30.62	-0.0006	31.64	0.0089
28.6	0.0003	29.62	-0.0001	30.64	-0.0014	31.66	0.0097
28.62	0.0006	29.64	0.0018	30.66	-0.0044	31.68	0.0072
28.64	0.0011	29.66	-0.0006	30.68	-0.0084	31.7	0.0015
28.66	0.0019	29.68	-0.0059	30.7	-0.0102	31.72	-0.0038
28.68	0.0046	29.7	-0.0113	30.72	-0.0093	31.74	-0.0055
28.7	0.0086	29.72	-0.0139	30.74	-0.0086	31.76	-0.0025
28.72	0.0115	29.74	-0.012	30.76	-0.0091	31.78	0.0019
28.74	0.0081	29.76	-0.0064	30.78	-0.0086	31.8	0.0042
28.76	0.0058	29.78	-0.0004	30.8	-0.0073	31.82	0.0046
28.78	0.0057	29.8	0.0049	30.82	-0.0053	31.84	0.002
28.8	0.0093	29.82	0.0043	30.84	-0.0033	31.86	-0.0027
28.82	0.0137	29.84	0.0018	30.86	-0.0013	31.88	-0.0054
28.84	0.017	29.86	0.0037	30.88	-0.0026	31.9	-0.0045
28.86	0.0195	29.88	0.0039	30.9	-0.0008	31.92	-0.0043
28.88	0.0186	29.9	0.0033	30.92	-0.002	31.94	-0.0053
28.9	0.017	29.92	0.0017	30.94	-0.0073	31.96	-0.0031
28.92	0.0177	29.94	0.0001	30.96	-0.01	31.98	-0.0015
28.94	0.0195	29.96	-0.0017	30.98	-0.0086	32	-0.0018
28.96	0.0202	29.98	-0.0036	31	-0.0061	32.02	-0.0025
28.98	0.0171	30	-0.0085	31.02	-0.0038	32.04	-0.0045
29	0.0152	30.02	-0.0117	31.04	-0.0003	32.06	-0.0044
29.02	0.014	30.04	-0.0042	31.06	-0.0017	32.08	-0.0022
29.04	0.0109	30.06	0.0032	31.08	-0.0047	32.1	0.0013
29.06	0.0049	30.08	0.0063	31.1	-0.0082	32.12	0.0046
29.08	0.0002	30.1	0.0047	31.12	-0.0097	32.14	0.0038
29.1	-0.0034	30.12	-0.0017	31.14	-0.0083	32.16	0.0044
29.12	-0.0056	30.14	-0.006	31.16	-0.0066	32.18	0.0058
29.14	-0.0032	30.16	-0.0047	31.18	-0.008	32.2	0.0045
29.16	0.0024	30.18	-0.0026	31.2	-0.0103	32.22	0.0037
29.18	0.0059	30.2	0.0031	31.22	-0.0107	32.24	0.0015
29.2	0.0059	30.22	0.0079	31.24	-0.0059	32.26	-0.0013
29.22	0.0048	30.24	0.0056	31.26	-0.0016	32.28	-0.0008
29.24	0.0016	30.26	0.0008	31.28	0.0004	32.3	0.0042
29.26	-0.0008	30.28	-0.0022	31.3	0.0028	32.32	0.0069
29.28	-0.0034	30.3	-0.0041	31.32	0.0046	32.34	0.0059
29.3	-0.0033	30.32	-0.0045	31.34	0.0066	32.36	0.0019
29.32	0.0005	30.34	-0.0007	31.36	0.0067	32.38	-0.0002
29.34	0.0046	30.36	0.0046	31.38	0.0037	32.4	0.0012
29.36	0.0059	30.38	0.0059	31.4	-0.0007	32.42	0.0031
29.38	0.0053	30.4	0.0001	31.42	-0.0039	32.44	0.0057
29.4	0.0042	30.42	-0.0045	31.44	-0.0031	32.46	0.0052
29.42	0.0043	30.44	-0.0052	31.46	0.0013	32.48	0.0051
29.44	0.0031	30.46	-0.0053	31.48	0.0025	32.5	0.0071
29.46	-0.002	30.48	-0.0055	31.5	0.0055	32.52	0.0103
29.48	-0.007	30.5	-0.0049	31.52	0.006	32.54	0.0114
29.5	-0.0066	30.52	-0.0016	31.54	0.0047	32.56	0.0127
29.52	-0.0061	30.54	0.0003	31.56	0.0053	32.58	0.0139
29.54	-0.0063	30.56	0.0031	31.58	0.005	32.6	0.0117
29.56	-0.0066	30.58	0.0014	31.6	0.0053	32.62	0.0105

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
32.64	0.011	33.66	-0.0033	34.68	0.0078	35.7	0
32.66	0.0084	33.68	-0.0058	34.7	0.0083	35.72	-0.0001
32.68	0.0031	33.7	-0.0076	34.72	0.0086	35.74	-0.0002
32.7	0.0018	33.72	-0.012	34.74	0.0088	35.76	-0.0004
32.72	0.005	33.74	-0.0138	34.76	0.0091	35.78	0.0007
32.74	0.0044	33.76	-0.0127	34.78	0.0092	35.8	0.0018
32.76	0.003	33.78	-0.0103	34.8	0.0082	35.82	0.0001
32.78	0.0029	33.8	-0.0095	34.82	0.0075	35.84	-0.0008
32.8	0.0014	33.82	-0.0118	34.84	0.0054	35.86	0.0001
32.82	0.0002	33.84	-0.0139	34.86	0.003	35.88	0.0009
32.84	0.0004	33.86	-0.017	34.88	0.0015	35.9	0.0029
32.86	0.0018	33.88	-0.0193	34.9	0	35.92	-0.0004
32.88	0.0033	33.9	-0.0181	34.92	0.001	35.94	-0.0036
32.9	0.0036	33.92	-0.0155	34.94	0.0034	35.96	-0.0028
32.92	0.0021	33.94	-0.0144	34.96	0.0032	35.98	-0.0001
32.94	0.0012	33.96	-0.0148	34.98	0.0006	36	0.002
32.96	0.0027	33.98	-0.0175	35	0.0012	36.02	0.0026
32.98	0.0039	34	-0.0177	35.02	0.0035	36.04	0.0016
33	0.0065	34.02	-0.0152	35.04	0.0042	36.06	-0.0011
33.02	0.0085	34.04	-0.0123	35.06	0.0031	36.08	-0.0025
33.04	0.0091	34.06	-0.0099	35.08	0.0005	36.1	-0.0028
33.06	0.0081	34.08	-0.0087	35.1	-0.0028	36.12	0.0008
33.08	0.008	34.1	-0.0062	35.12	-0.0041	36.14	0.0018
33.1	0.0088	34.12	-0.0057	35.14	-0.0047	36.16	0.0018
33.12	0.0072	34.14	-0.0056	35.16	-0.0036	36.18	0.0008
33.14	0.006	34.16	-0.0044	35.18	-0.0034	36.2	0.0003
33.16	0.0035	34.18	-0.0034	35.2	-0.0032	36.22	0.0022
33.18	0.0028	34.2	-0.0008	35.22	-0.0024	36.24	0.0047
33.2	0.0001	34.22	-0.0011	35.24	-0.0049	36.26	0.0065
33.22	0.0009	34.24	-0.0005	35.26	-0.0067	36.28	0.0075
33.24	0.003	34.26	-0.0008	35.28	-0.0086	36.3	0.0077
33.26	0.0045	34.28	-0.0015	35.3	-0.008	36.32	0.007
33.28	0.0046	34.3	-0.0006	35.32	-0.0053	36.34	0.0085
33.3	0.0035	34.32	0.0012	35.34	-0.0038	36.36	0.0109
33.32	0.0031	34.34	0.002	35.36	-0.0044	36.38	0.0113
33.34	0.0014	34.36	0.002	35.38	-0.0049	36.4	0.0108
33.36	0.0022	34.38	0.004	35.4	-0.0037	36.42	0.01
33.38	0.0007	34.4	0.0038	35.42	-0.0022	36.44	0.0091
33.4	0.0007	34.42	0.0029	35.44	-0.0007	36.46	0.0089
33.42	0.0016	34.44	0.0045	35.46	-0.0003	36.48	0.0091
33.44	0.003	34.46	0.0061	35.48	-0.0015	36.5	0.0096
33.46	0.0023	34.48	0.0069	35.5	-0.0005	36.52	0.0085
33.48	-0.0006	34.5	0.0106	35.52	-0.0016	36.54	0.0068
33.5	-0.0034	34.52	0.0119	35.54	-0.0024	36.56	0.0063
33.52	-0.0057	34.54	0.0112	35.56	-0.0003	36.58	0.0043
33.54	-0.0086	34.56	0.012	35.58	-0.0015	36.6	0.0014
33.56	-0.0071	34.58	0.0109	35.6	-0.0027	36.62	0.0012
33.58	-0.0045	34.6	0.0084	35.62	-0.0046	36.64	0.0014
33.6	-0.0046	34.62	0.0065	35.64	-0.0045	36.66	0.0028
33.62	-0.0043	34.64	0.0055	35.66	-0.0034	36.68	0.0031
33.64	-0.0041	34.66	0.0067	35.68	-0.0014	36.7	0.0016

Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)	Time (s)	Acceleration (g)
36.72	0.0004	37.74	-0.0027	38.76	0.0012	39.78	0
36.74	0.0006	37.76	-0.0019	38.78	0.0008	39.8	-0.0001
36.76	0.0017	37.78	-0.0006	38.8	0.0007	39.82	-0.0001
36.78	0.0012	37.8	-0.0005	38.82	0.0011	39.84	-0.0001
36.8	0	37.82	0	38.84	0.0013	39.86	-0.0002
36.82	-0.0003	37.84	0	38.86	0.0012	39.88	-0.0002
36.84	-0.0003	37.86	-0.0002	38.88	0.0011	39.9	-0.0003
36.86	-0.0019	37.88	-0.0002	38.9	0.001	39.92	-0.0003
36.88	-0.0034	37.9	0.0002	38.92	0.0007	39.94	-0.0003
36.9	-0.0022	37.92	0.0003	38.94	0.0008	39.96	-0.0004
36.92	-0.0005	37.94	-0.0011	38.96	0.0009	39.98	-0.0004
36.94	0.0006	37.96	-0.0007	38.98	0.0009		
36.96	0.0008	37.98	-0.0001	39	0.0012		
36.98	-0.0002	38	0	39.02	0.0011		
37	-0.0006	38.02	-0.0006	39.04	0.0008		
37.02	0.0004	38.04	-0.0021	39.06	0.0008		
37.04	-0.0003	38.06	-0.0039	39.08	0.0008		
37.06	-0.002	38.08	-0.0038	39.1	0.0011		
37.08	-0.0029	38.1	-0.0027	39.12	0.0013		
37.1	-0.0016	38.12	-0.0014	39.14	0.0015		
37.12	-0.0006	38.14	-0.0002	39.16	0.0017		
37.14	0.0004	38.16	-0.0003	39.18	0.0018		
37.16	0.0015	38.18	-0.0001	39.2	0.0018		
37.18	-0.0003	38.2	0	39.22	0.0018		
37.2	-0.0021	38.22	-0.0001	39.24	0.0016		
37.22	-0.0032	38.24	-0.0009	39.26	0.0015		
37.24	-0.0027	38.26	-0.0022	39.28	0.0014		
37.26	-0.0026	38.28	-0.003	39.3	0.0014		
37.28	-0.0031	38.3	-0.0026	39.32	0.0014		
37.3	-0.0038	38.32	-0.0021	39.34	0.0014		
37.32	-0.0038	38.34	-0.0017	39.36	0.0013		
37.34	-0.0043	38.36	-0.0015	39.38	0.0013		
37.36	-0.0042	38.38	-0.0013	39.4	0.0012		
37.38	-0.0047	38.4	-0.0015	39.42	0.001		
37.4	-0.0066	38.42	-0.0019	39.44	0.0009		
37.42	-0.0076	38.44	-0.0015	39.46	0.0008		
37.44	-0.008	38.46	-0.0014	39.48	0.0007		
37.46	-0.0078	38.48	-0.0015	39.5	0.0007		
37.48	-0.0067	38.5	-0.0011	39.52	0.0006		
37.5	-0.0035	38.52	-0.0008	39.54	0.0005		
37.52	-0.0021	38.54	-0.0008	39.56	0.0003		
37.54	-0.0021	38.56	-0.0006	39.58	0.0002		
37.56	-0.0028	38.58	-0.0003	39.6	0.0002		
37.58	-0.0042	38.6	0.0002	39.62	0.0001		
37.6	-0.0043	38.62	0.0004	39.64	0.0001		
37.62	-0.0031	38.64	0.0006	39.66	0.0001		
37.64	-0.002	38.66	0.0004	39.68	0.0001		
37.66	-0.0007	38.68	0	39.7	0.0001		
37.68	-0.001	38.7	0.0004	39.72	0		
37.7	-0.0008	38.72	0.0006	39.74	0		
37.72	-0.0012	38.74	0.0009	39.76	0		

Appendix C: Maximum Displacements in the Unclad Models and Clad Models

Measurement of Displacement of Lateral Stayed Connection Model in the Y Direction Loading

Y Direction		Absolute Max Displacement (ft)					Interstory Displacement (ft)				
Joint	Story	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
765	20	0.135345	0.131755	0.122453	0.112584	0.112314	0.007189	0.006611	0.006439	0.005530	0.005504
755	19	0.128156	0.125144	0.116014	0.107054	0.106810	0.007370	0.006799	0.006480	0.005532	0.005531
754	18	0.120786	0.118345	0.109534	0.101522	0.101279	0.007591	0.007049	0.006519	0.005546	0.005546
753	17	0.113195	0.111296	0.103015	0.095976	0.095733	0.007571	0.007203	0.006539	0.005546	0.005545
752	16	0.105624	0.104093	0.096476	0.090430	0.090188	0.007703	0.007331	0.006161	0.005561	0.005488
751	15	0.097921	0.096762	0.090315	0.084869	0.084700	0.007685	0.007427	0.006070	0.005561	0.005489
750	14	0.090236	0.089335	0.084245	0.079308	0.079211	0.007854	0.007554	0.006163	0.005584	0.005512
749	13	0.082382	0.081781	0.078082	0.073724	0.073699	0.007659	0.007529	0.006209	0.005569	0.005499
748	12	0.074723	0.074252	0.071873	0.068155	0.068200	0.007833	0.007602	0.006305	0.005605	0.005538
747	11	0.066890	0.066650	0.065568	0.062550	0.062662	0.007579	0.007466	0.006328	0.005588	0.005524
746	10	0.059311	0.059184	0.059240	0.056962	0.057138	0.007503	0.007394	0.006364	0.005599	0.005541
745	9	0.051808	0.051790	0.052876	0.051363	0.051597	0.007403	0.007297	0.006374	0.005610	0.005559
744	8	0.044405	0.044493	0.046502	0.045753	0.046038	0.007145	0.007075	0.006328	0.005608	0.005565
743	7	0.037260	0.037418	0.040174	0.040145	0.040473	0.006792	0.006740	0.006228	0.005600	0.005566
742	6	0.030468	0.030678	0.033946	0.034545	0.034907	0.006360	0.006347	0.006065	0.005584	0.005562
741	5	0.024108	0.024331	0.027881	0.028961	0.029345	0.006023	0.006007	0.005856	0.005585	0.005574
740	4	0.018085	0.018324	0.022025	0.023376	0.023771	0.005585	0.005546	0.005562	0.005572	0.005577
739	3	0.012500	0.012778	0.016463	0.017804	0.018194	0.004849	0.004704	0.005208	0.005568	0.005585
738	2	0.007651	0.008074	0.011255	0.012236	0.012609	0.005849	0.006172	0.009376	0.009002	0.009644
737	1	0.001802	0.001902	0.001879	0.003234	0.002965	0.001802	0.001902	0.001879	0.003234	0.002965
736	0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

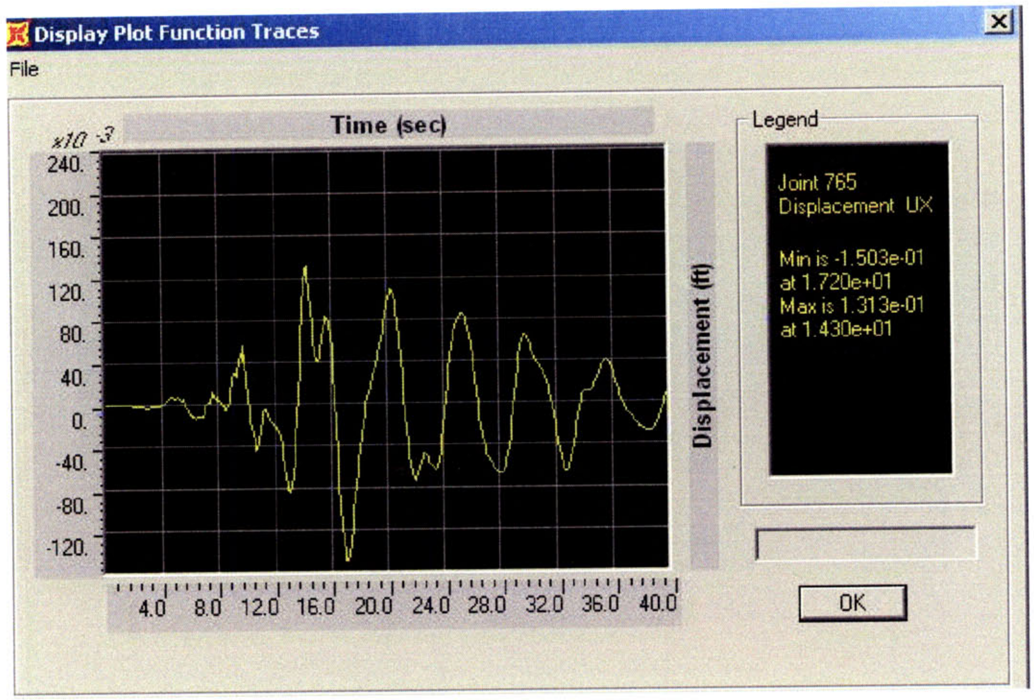
Measurement of Displacement of Rocking Connection Model in the Y Direction Loading

Y Direction		Absolute Max Displacement (ft)					Interstory Displacement (ft)				
Joint	Story	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
765	20	0.135345	0.131756	0.122465	0.112591	0.112319	0.007189	0.006612	0.006441	0.005531	0.005504
755	19	0.128156	0.125144	0.116024	0.107060	0.106815	0.007370	0.006798	0.006481	0.005533	0.005531
754	18	0.120786	0.118346	0.109543	0.101527	0.101284	0.007591	0.007049	0.006521	0.005546	0.005546
753	17	0.113195	0.111297	0.103022	0.095981	0.095738	0.007571	0.007204	0.006540	0.005547	0.005546
752	16	0.105624	0.104093	0.096482	0.090434	0.090192	0.007703	0.007331	0.006162	0.005561	0.005489
751	15	0.097921	0.096762	0.090320	0.084873	0.084703	0.007685	0.007427	0.006070	0.005561	0.005488
750	14	0.090236	0.089335	0.084250	0.079312	0.079215	0.007854	0.007554	0.006165	0.005585	0.005513
749	13	0.082382	0.081781	0.078085	0.073727	0.073702	0.007659	0.007529	0.006209	0.005569	0.005499
748	12	0.074723	0.074252	0.071876	0.068158	0.068203	0.007833	0.007602	0.006306	0.005606	0.005539
747	11	0.066890	0.066650	0.065570	0.062552	0.062664	0.007579	0.007466	0.006329	0.005588	0.005524
746	10	0.059311	0.059184	0.059241	0.056964	0.057140	0.007503	0.007394	0.006364	0.005599	0.005541
745	9	0.051808	0.051790	0.052877	0.051365	0.051599	0.007403	0.007297	0.006374	0.005611	0.005559
744	8	0.044405	0.044493	0.046503	0.045754	0.046040	0.007145	0.007075	0.006329	0.005609	0.005566
743	7	0.037260	0.037418	0.040174	0.040145	0.040474	0.006792	0.006740	0.006228	0.005600	0.005567
742	6	0.030468	0.030678	0.033946	0.034545	0.034907	0.006360	0.006347	0.006065	0.005584	0.005561
741	5	0.024108	0.024331	0.027881	0.028961	0.029346	0.006023	0.006007	0.005856	0.005585	0.005575
740	4	0.018085	0.018324	0.022025	0.023376	0.023771	0.005585	0.005546	0.005563	0.005572	0.005577
739	3	0.012500	0.012778	0.016462	0.017804	0.018194	0.004849	0.004704	0.005207	0.005569	0.005586
738	2	0.007651	0.008074	0.011255	0.012235	0.012608	0.005849	0.006172	0.009376	0.009001	0.009642
737	1	0.001802	0.001902	0.001879	0.003234	0.002966	0.001802	0.001902	0.001879	0.003234	0.002966
736	0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

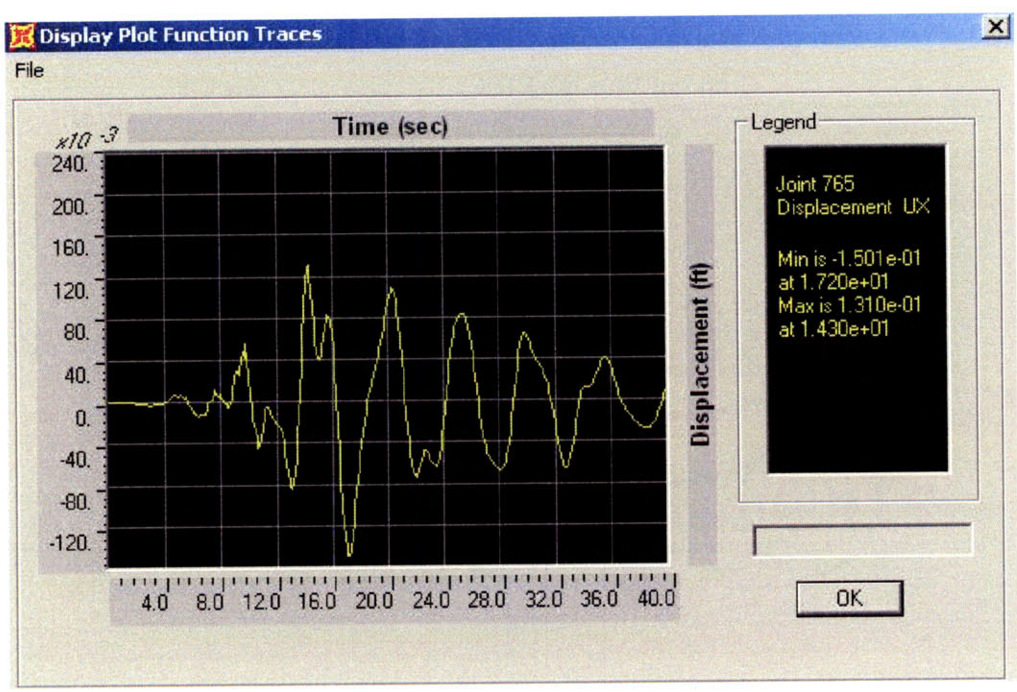
Measurement of Displacement of Lateral Stayed Connection Model in the X Direction Loading

X Direction		Absolute Max Displacement (ft)					Interstory Displacement (ft)				
Joint	Story	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)	UnClad	Clad (k=1x10^3k/in)	Clad (k=1x10^5 k/in)	Clad (k=1x10^7 k/in)	Clad (k=1x10^9 k/in)
765	20	0.150301	0.150141	0.150297	0.150630	0.150642	0.008583	0.008504	0.008352	0.008396	0.008402
755	19	0.141718	0.141637	0.141945	0.142234	0.142240	0.014060	0.013986	0.013960	0.013956	0.013956
754	18	0.127658	0.127651	0.127985	0.128278	0.128284	0.018216	0.018156	0.018243	0.018257	0.018257
753	17	0.109442	0.109495	0.109742	0.110021	0.110027	0.016458	0.016505	0.016706	0.016839	0.016840
752	16	0.092984	0.09299	0.093036	0.093182	0.093187	0.011343	0.011244	0.011149	0.011213	0.011217
751	15	0.081641	0.081746	0.081887	0.081969	0.081970	0.009061	0.009003	0.009120	0.009278	0.009281
750	14	0.072580	0.072743	0.072767	0.072691	0.072689	0.002616	0.002773	0.003405	0.004011	0.004023
749	13	0.069964	0.06997	0.069362	0.068680	0.068666	0.003234	0.003163	0.003063	0.002965	0.002964
748	12	0.066730	0.066807	0.066299	0.065715	0.065702	0.002627	0.002660	0.002775	0.002856	0.002857
747	11	0.064103	0.064147	0.063524	0.062859	0.062845	0.002986	0.002935	0.002881	0.002811	0.002810
746	10	0.061117	0.061212	0.060643	0.060048	0.060035	0.003378	0.003339	0.003287	0.003224	0.003222
745	9	0.057739	0.057873	0.057356	0.056824	0.056813	0.003719	0.003691	0.003641	0.003583	0.003582
744	8	0.054020	0.054182	0.053715	0.053241	0.053231	0.003813	0.003794	0.003746	0.003695	0.003695
743	7	0.050207	0.050388	0.049969	0.049546	0.049536	0.003855	0.003847	0.003798	0.003752	0.003750
742	6	0.046352	0.046541	0.046171	0.045794	0.045786	0.004580	0.004585	0.004530	0.004482	0.004481
741	5	0.041772	0.041956	0.041641	0.041312	0.041305	0.004710	0.004697	0.004638	0.004594	0.004593
740	4	0.037062	0.037259	0.037003	0.036718	0.036712	0.004600	0.004642	0.004599	0.004554	0.004553
739	3	0.032462	0.032617	0.032404	0.032164	0.032159	0.004923	0.004986	0.004943	0.004892	0.004892
738	2	0.027539	0.027631	0.027461	0.027272	0.027267	0.024225	0.024309	0.024176	0.024018	0.024013
737	1	0.003314	0.003322	0.003285	0.003254	0.003254	0.003314	0.003322	0.003285	0.003254	0.003254
736	0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

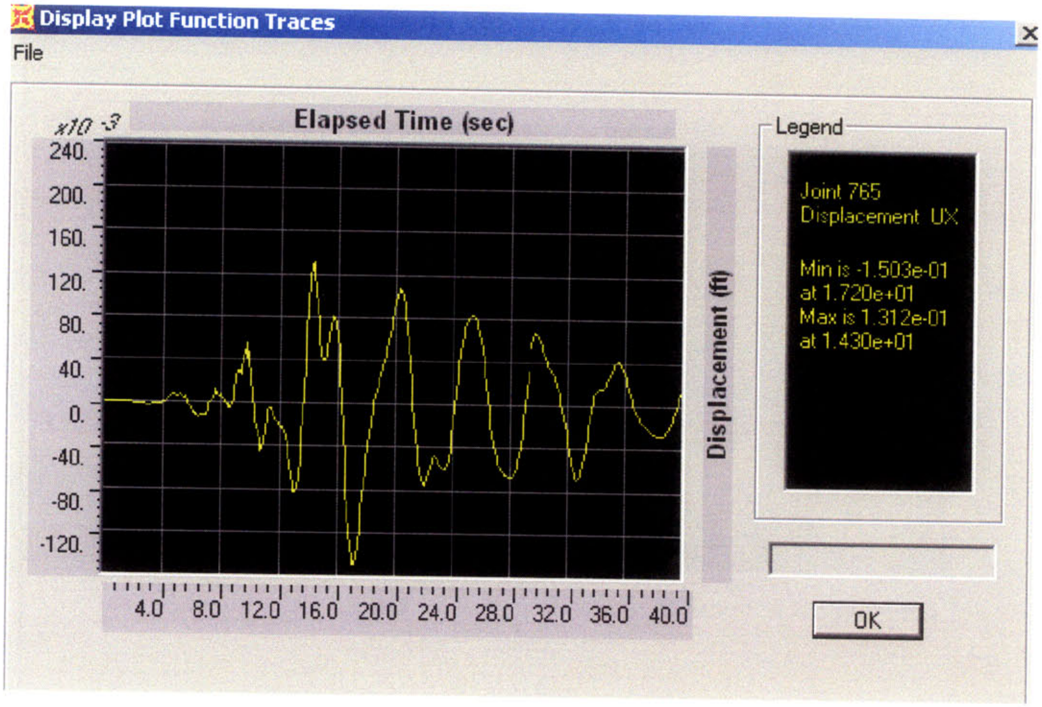
Appendix D: Time-Displacement History Plots



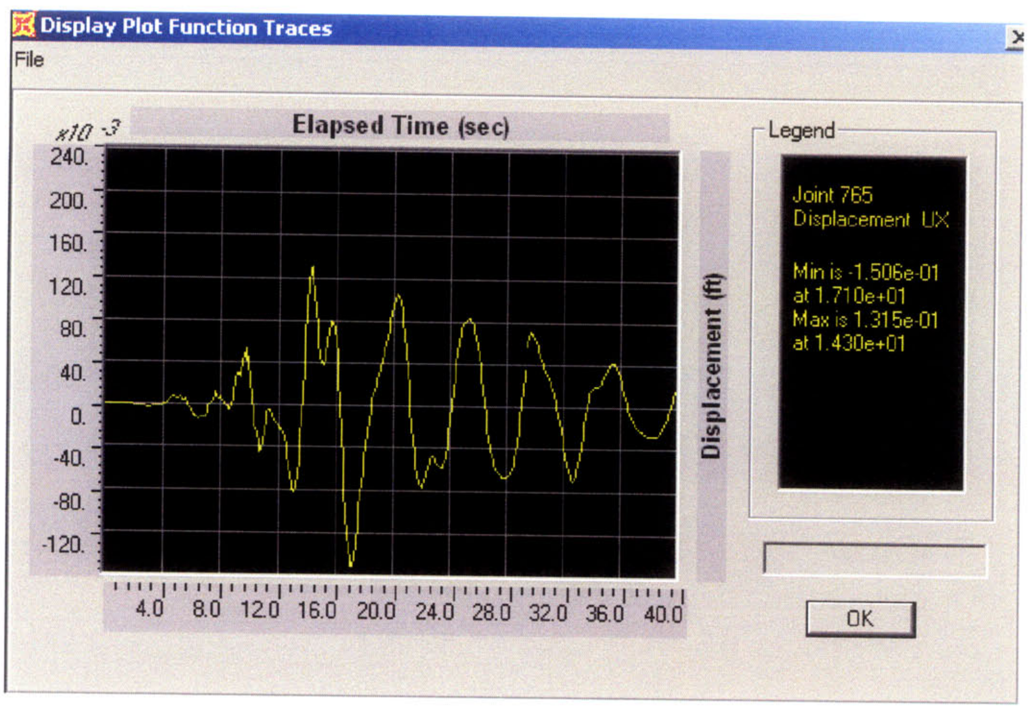
Time-Displacement History of an unclad model in the *x* direction loading



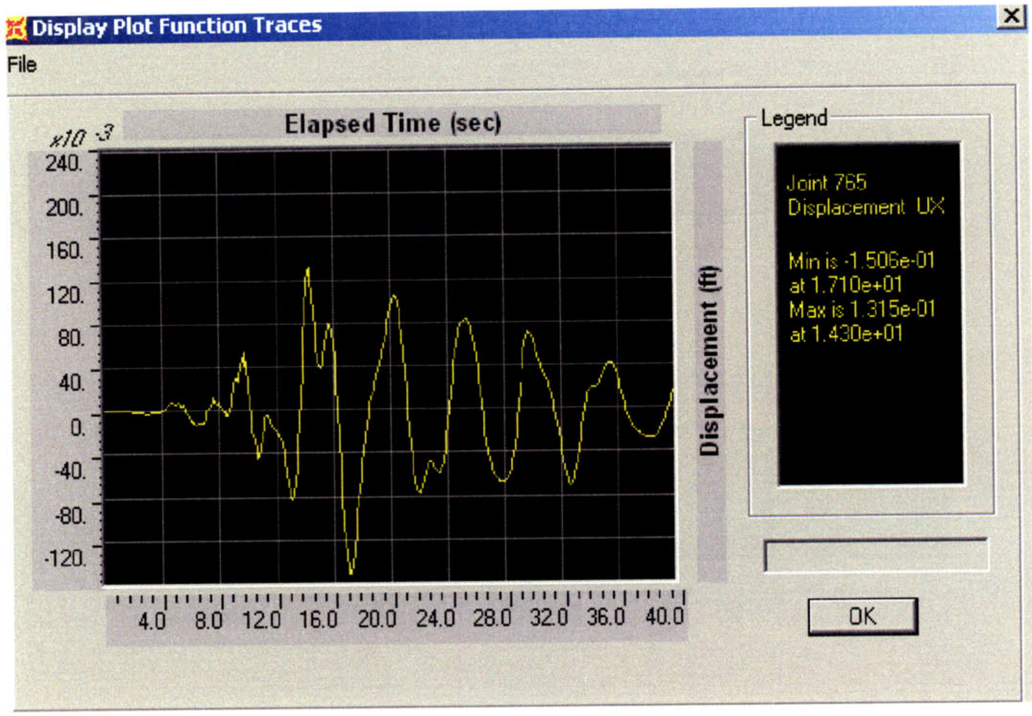
Time-Displacement History of a clad ($k=1x10^3$ k/in) model in the *x* direction loading



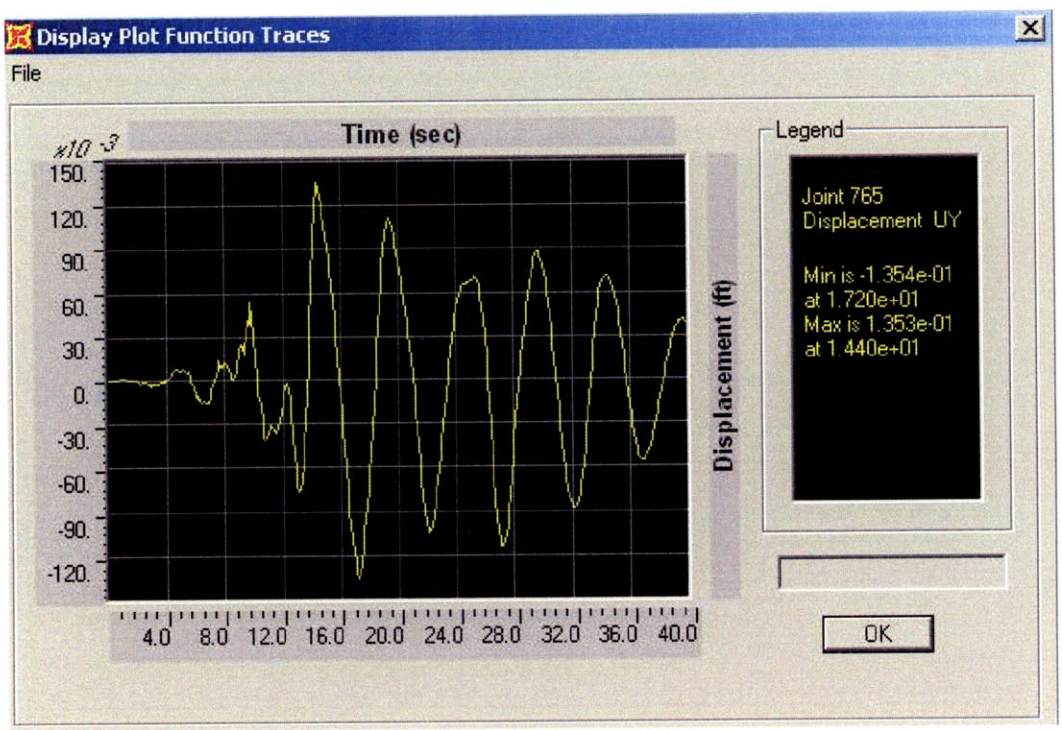
Time-Displacement History of a clad (k=1x10^5 k/in) model in the *x* direction loading



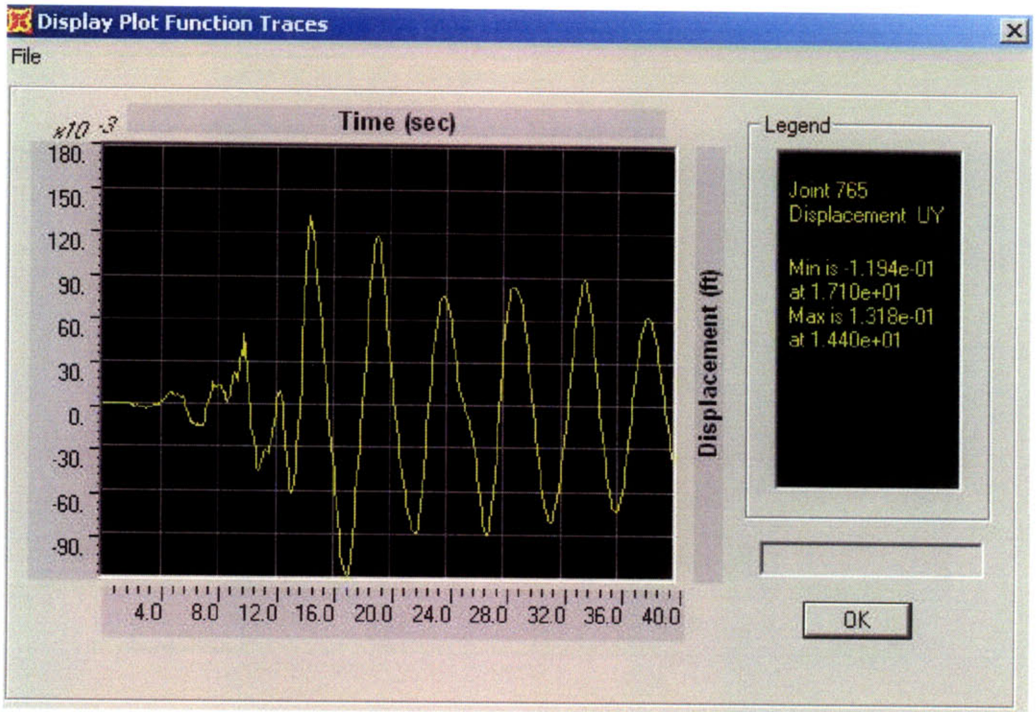
Time-Displacement History of a clad (k=1x10^7 k/in) model in the *x* direction loading



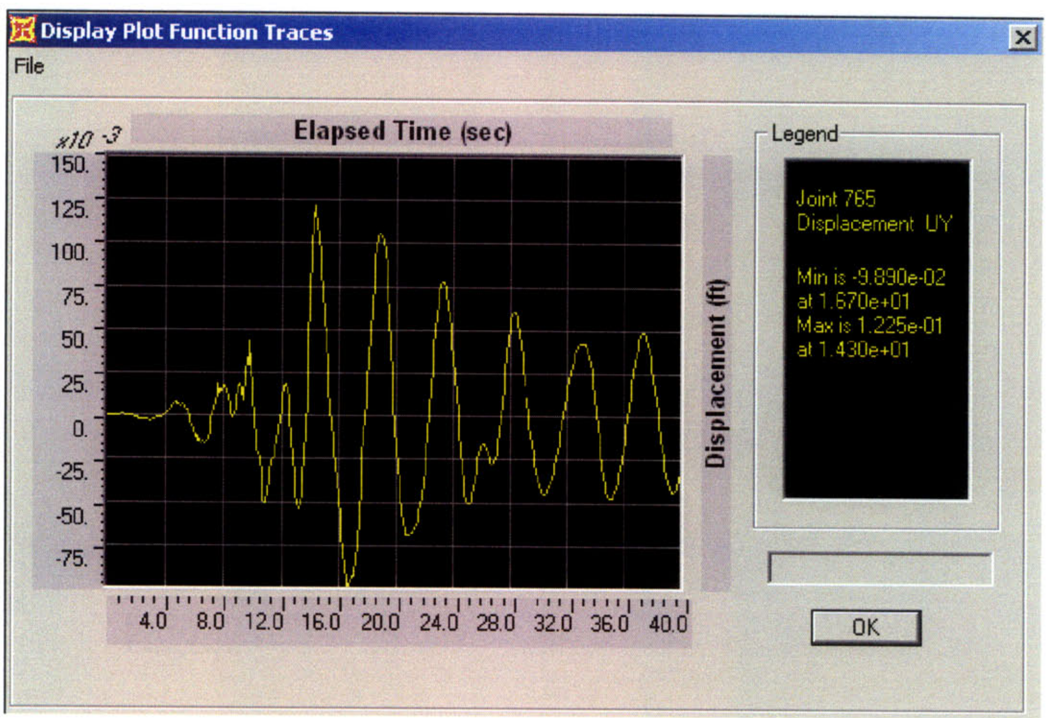
Time-Displacement History of a clad (k=1x10^9 k/in) model in the *x* direction loading



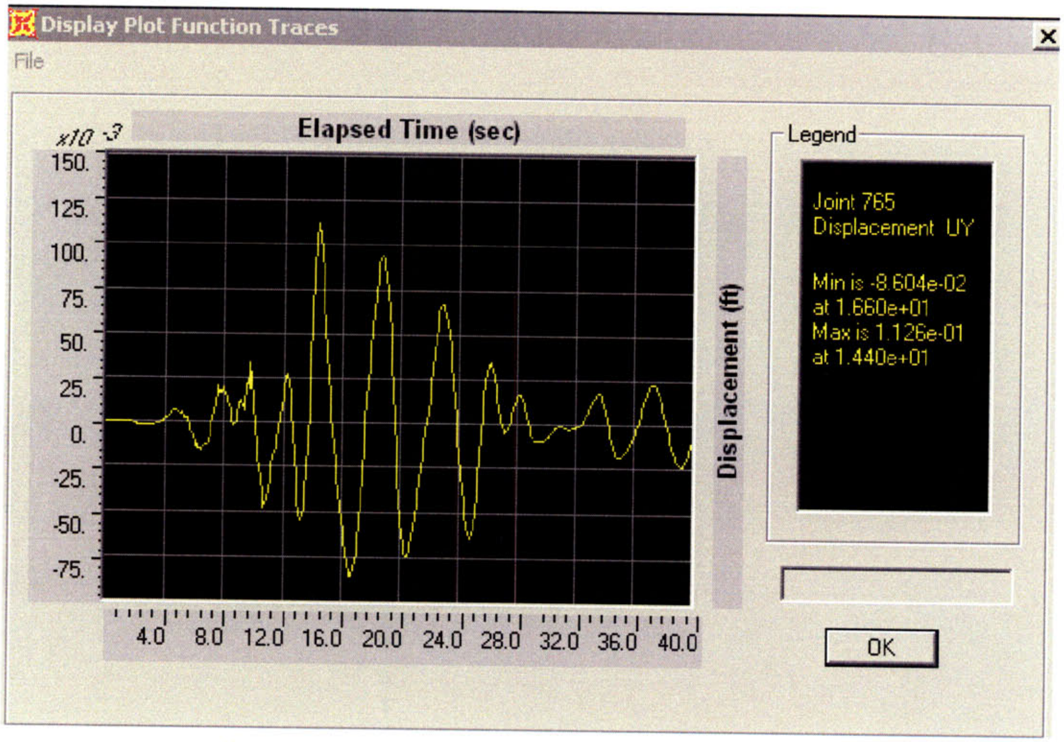
Time-Displacement History of an unclad model in the *y* direction loading



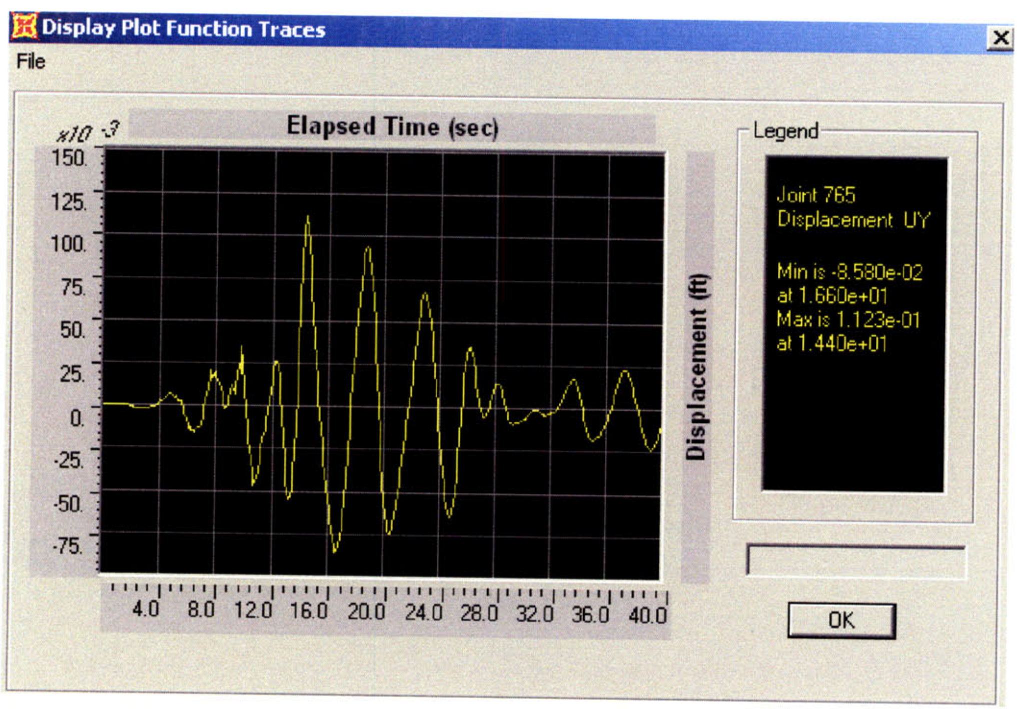
Time-Displacement History of a clad (k=1x10^3 k/in) model in the *y* direction loading



Time-Displacement History of a clad (k=1x10^5 k/in) model in the *y* direction loading



Time-Displacement History of a clad (k=1x10^7 k/in) model in the *y* direction loading



Time-Displacement History of a clad (k=1x10^9 k/in) model in the *y* direction loading